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THE STREAMS OF THE COASTAL PLAIN OF ALABAMA AND THE LAFAYETTE PROBLEM

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ABSTRACT

The Alabama and Tombigbee rivers, which drain most of Alabama and small portions of Georgia and Mississippi, converge at Mobile Bay. The Alabama River appears to have been formed by the diversion of streams which were formerly through-flowing. It is suggested that downwarping in southwestern Alabama caused the convergence of the drainage. The distribution of the Lafayette gravels aids in the interpretation of the history of the streams.

The streams of Alabama belong to two great systems: the northern border of the state is drained by the Tennessee River which, by an anomalous course, is indirectly tributary to the Mississippi through the lower part of the Ohio; to the south of this drainage area, the streams flow toward the Gulf of Mexico. The divide between the two systems is believed to have been maintained since the close of Cretaceous time (see Fig. 1).[1]

The streams which flow to the Gulf Coast have an interesting history which is here explained in accordance with the geologic development of the Coastal Plain. This involves the question of stream diversion in the formation of the Alabama River and the consideration of the "Lafayette formation" in Alabama which has been a problem of many years' standing.

When the coastal portion of Alabama emerged at the close of the Cretaceous, the streams on it presumably flowed to the Gulf of

[1] George I. Adams, "The Course of the Tennessee River and the Physiography of the Southern Appalachian Region," *Jour. of Geol.*, Vol. XXXVI (1928), pp. 481–93.

Mexico and probably entered it at the now submerged border of the continent. Considerable time elapsed before the transgression of the sea in which Eocene deposits were laid down. The streams of that interval are probably in part represented, at least in a general way, by the head-water courses of the present principal drainages which flow toward the Coastal Plain. The streams of western Alabama were presumably consequent on the newly emerged Cretaceous formations, while those of the eastern part of Alabama and the Chattahoochee, which forms the border of the state, may have been adjusted to structure, where, in their upper reaches, they flowed on the older rocks; but their prolongations to the coast were consequent channels as were those of the streams of the western part of the state. Erosional agencies were effective during that time, for the land stood relatively high. The Tennessee River presumably deepened its newly established valley. The consequent streams flowing to the gulf incised the upper portions of their valleys, while the revived streams on the older rocks in the eastern part of the state were active in establishing a new base-level. The materials eroded were deposited beyond the continental shelf, so that there is no available record of them. Following this condition came the transgression of the Tertiary sea.

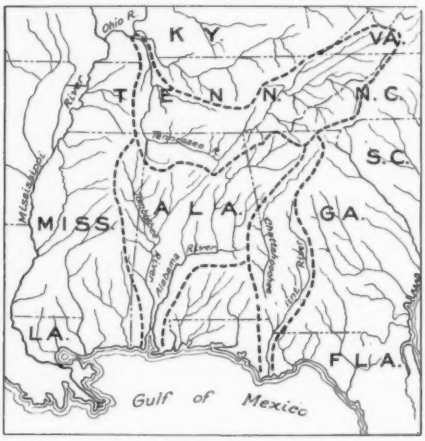

FIG. 1.—Map showing the drainage systems of Alabama.

The present inner border of the Tertiary corresponds with the outcrop of the Clayton formation from the Georgia state line westward for two-thirds of the distance across Alabama, to where there is an overlap, and it also outcrops at places in Mississippi. The Clayton contains marine limestones, and since it is the lowest Eocene

deposit and has been considerably eroded, it is reasonable to assume that the coast in Clayton time was 30 miles or so inland from the present line of outcrop of the formation, as is represented in Figure 2.

The Coastal Plain in the early Eocene was low lying and relatively narrow. The streams had low gradients, and the deposits of that time, as now exposed in Alabama, contain no coarse sediments. In the western part of the state there are some deltaic sandstones which have been included in the base of the Nanafalia formation of the Wilcox group; on revision, however, they may be assigned to the Midway group which is below the Wilcox. There is evidence of a slight emergence and a still-standing after the deposition of these sandstones. This interval is marked by the deposition of lignite beds which range up to 20 feet in thickness and are found at intervals nearly across the state. It was also the time of origin of the bauxite deposits which are found at practically the same horizon as the lignites.

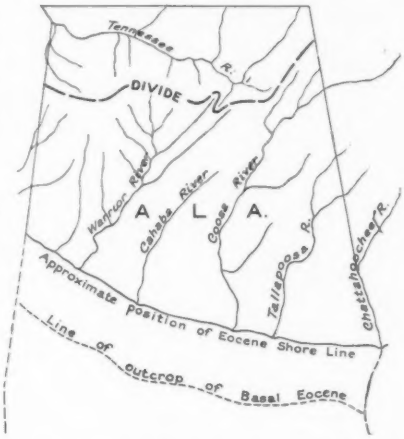

FIG. 2.—Sketch showing the probable drainage of Alabama at the beginning of the Eocene.

These bauxites occur in Mississippi and from points near the eastern border of Alabama eastward to central Georgia. Bauxite deposits contemporaneous with these occurring inland along the anticlinal valleys serve to mark the Eocene base-level in northern Alabama, northeastern Georgia, and near Chattanooga, Tennessee.[1]

During the deposition of the lignite and the formation of the bauxite, the southeastern angle of the continent was submerged and the Gulf Stream then probably swept across what is now southern Alabama and southern Georgia. The coast was low lying, and the

[1] George I. Adams, "Bauxite Deposits of the Southern States," *Econ. Geol.*, Vol. XXII, No. 6 (1927), pp. 615–20.

climate, as is evidenced by the fossil plants, was humid and tropical —conditions favoring the formation of lignite and bauxite. This also explains the general absence of coarse sediments and conglomerate beds.

The succeeding Tertiary deposits are largely marine and are also devoid of conglomerates. Those of the Nanafalia (Wilcox group) which overlie the lignites are largely greensands filled with *Ostrea thirsae*, which indicates a transgression of the sea. Unimportant beds of lignite in the Bashi indicate temporary low coastal areas. The successive oscillations of the coast and the invasions or embayments of the sea continued without notable vertical movements of the land until the end of the Miocene.

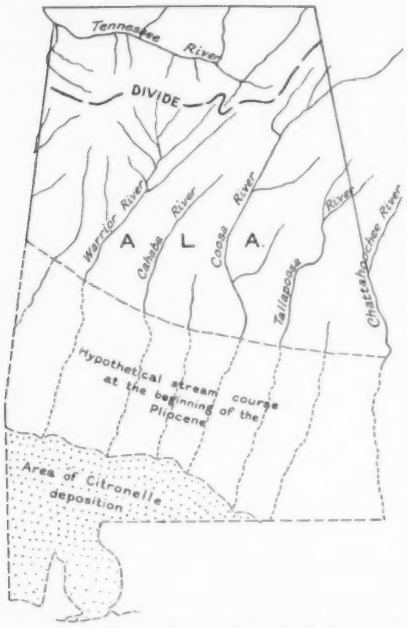

FIG. 3.—Sketch showing hypothetical coastal streams at the beginning of the Pliocene.

In the Pliocene there was a gradual elevation of the land which as it progressed increased the gradients of the streams and enabled them to transport coarse sediments, including eventually great quantities of gravel derived from the rocks along their upper courses. The rivers which had through-flowing and probably direct and nearly parallel channels (see Fig. 3) began to alter their courses soon after the beginning of the Pliocene, and the shifting and diversion of the streams which ensued resulted in important changes in the river systems.

The peculiarity of the present drainage (see Figs. 1 and 4) is most pronounced approximately in the latitude of Montgomery and west-

ward toward Selma. The Tallapoosa River changes its course from southward to westward and receives the Coosa near Montgomery, thus forming the Alabama River. The confluence of the Cahaba with the Alabama is just below Selma. Beyond this, the course of the Alabama toward the coast appears to be the natural continuation of the Cahaba River. These drainage courses suggest diversion and stream capture. The Chattahoochee River, on the eastern border of Alabama, maintained its course directly to the gulf, and the Warrior River, in the western part of the state, was a through-flowing stream. The question is: Why did not the Tallapoosa and the more important Coosa maintain independent courses parallel with the Chattahoochee and the Warrior-Tombigbee?

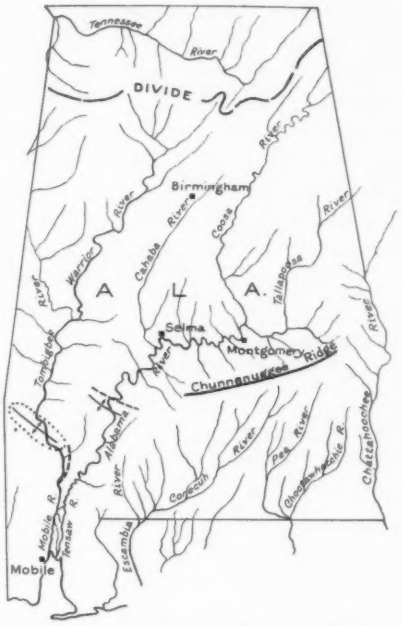

FIG. 4.—Map showing the position of Chunnenuggee Ridge and the relation of streams to structures in southwestern Alabama.

The Alabama River receives small tributaries from the south and southeast where it is flowing westward. They head at a divide known as Chunnenuggee Ridge (see Fig. 4), which extends from the western border of Russell County through the southeastern corner of Macon, diagonally through Bullock, through the southern part of Montgomery, and into Lowndes County.[1] Thence the divide continues in an irregular course into Butler and Wilcox counties. South of it, the drainage has a southwesterly direction to the Gulf of Mexico.

[1] Eugene A. Smith, "Geology of the Coastal Plain of Alabama," *Geol. Survey of Ala.* (1894), pp. 355–56 and 661.

The elevations on the higher portions of Chunnenuggee Ridge range between 400 and 500 feet. In the valley of the Alabama River, the altitude of the railway at Montgomery is 160 feet, and at Selma it is 127 feet. These elevations are near the river. The adjacent lowland developed on the easily eroded Cretaceous formations is at higher elevations.

Although Chunnenuggee Ridge is now conspicuous, the writer believes that at the beginning of the Pliocene, streams from the north flowed over the area it occupies, because he has found scattered pebbles south of it, such as could have been brought only by streams flowing from the area of the Crystallines. The drainages heading south of the divide, however, do not have the terrace and stream gravels which are characteristic of the through-flowing rivers of the Coastal Plain. It follows, therefore, that the streams which brought the scattered gravels from the Crystallines were soon diverted.[1]

In its typical portion, Chunnenuggee Ridge is a northward-facing escarpment containing some beds which are resistant to weathering, and it is natural to think that they might have assisted in stream diversions that resulted in the peculiarities of the Alabama River drainage. While certain beds of the Ripley are resistant to weathering, nevertheless the formation would presumably have yielded readily enough to stream action if there had been no other factors influencing the courses of the streams.

In the latitude of Montgomery and Selma the Alabama River flows on softer Cretaceous formations which favor stream capture, and it might be argued that these rocks are responsible for the diversion of the streams crossing them. This is reasonable, but this factor became important relatively late as is shown by the distribution of high-level stream gravels which must be considered in the problem.

At Collirene, twenty miles southeast of Selma, there are some hills which are outliers of the Chunnenuggee escarpment. On them there are coarse gravels which were noted by Thornton in a report

[1] Gravels have been hauled for surfacing and constructing roads in the part of the state under discussion. Not infrequently pebbles have been thrown into the fields along the roads. Such pebbles should not be confused with the old scattered gravels here mentioned.

by M. Tuomey[1] and redescribed by Langdon in a report by Eugene A. Smith.[2]

The writer visited Collirene and saw that these gravels, as reported, are for the most part quartz pebbles, with some chert pebbles showing Paleozoic fossils. They have therefore been derived from the Crystallines and Paleozoics, or possibly indirectly from the Tuscaloosa formation (basal Upper Cretaceous) or inland river-terrace deposits of early Tertiary origin. The elevation of these gravels was found to be 430 feet (aneroid) and apparently as high as portions of the escarpment 4 miles to the south. It was thought at the time that these gravels might have been deposited by a stream that crossed Chunnenuggee Ridge, but no continuation of the gravels was found on the main escarpment.

The gravels at Collirene at least furnish proof of important shifting in the stream channels in that part of Alabama, and since they are about 300 feet above Selma, they afford evidence of the vast amount of erosion which has taken place subsequent to their deposition.

There are other similar high-level gravel deposits which have a bearing on the problem of the drainages and which furnish additional proof that the present course of the Alabama River was attained after many shiftings of the streams to the north of Chunnenuggee Ridge.

As an explanation of why the Tallapoosa and Coosa do not have independent courses to the gulf parallel with the Chattahoochee and the Warrior-Tombigbee, the following suggestions are offered. When at the beginning of the Pliocene the Appalachian and Coastal Plain regions were elevated, the streams were at first probably through-flowing, as shown hypothetically in Figure 3. In the early Pliocene the streams had relatively low gradients and carried a relatively small amount of gravel. As the elevation progressed, the gradient of the rivers was increased so that the rivers flowed swiftly and transported an abundance of coarse sediments. At the same time there was a downwarping in southwestern Alabama which caused progres-

[1] *Second Biennial Report, Geological Survey of Alabama* (1858), p. 234.

[2] "Geology of the Coastal Plain of Alabama," *Geol. Survey of Ala.* (1894), pp. 427 and 581.

sive diversion of the Tallapoosa and Coosa rivers on the Cretaceous formations, and initiated the development of the lowland north of Chunnenuggee Ridge. It was then that the sediments deposited as coalescing deltas began the formation of the coastal deposits which were once called Lafayette and now, on the gulf border, are mapped as the Citronelle. The Alabama and Tombigbee rivers contributed quartz and chert gravels to the Citronelle, but the decapitated streams south of Chunnenuggee Ridge did not.

The deposition of the Citronelle has been discussed by Stephenson.[1] His mapping of it in Alabama is evidently based in part on the mapping by Cooke.[2] The Citronelle is the only Coastal Plain deposit that contains a conspicuous amount of gravel from the Crystallines, and its Pliocene age makes it very significant in the problem of the development of the coastal streams.

Warping of the Coastal Plain is indicated by a study of such altitudes as are on record and by barometric readings. These show that the eastern part of Chunnenuggee Ridge stands higher than the western part and that the divide to the west of the Chattahoochee River is relatively high with respect to the divides between the streams farther west. The southwestward course of the streams in Alabama south of Chunnenuggee Ridge implies an inclination of the surface in the direction of their flow.

More conclusive proof of the deformation is found in the faults and folds of the Coastal Plain. No important faults or folds have been mapped in southeastern Alabama, but in the southwestern part of the state the Hatchetigbee anticline and the Jackson fault are well-known structures (see Fig. 4). The Hatchetigbee anticline lies athwart the Tombigbee River, and the stream probably maintained its course while the fold was formed. To the northeast of this fold, the Alabama River crosses the Bethel fault, adjusting its course to the displacement for several miles. It also crosses the Peachtree anticline which owes its reverse dip to downthrow along the Bethel fault

[1] Lloyd W. Stephenson, "Major Marine Transgressions and Regressions and Structural Features of the Gulf Coastal Plain," *Amer. Jour. of Sci.*, Vol. XVI (October, 1928), Fig. 10, p. 292.

[2] "Geological Map of Alabama, 1926," *Geol. Survey of Ala.; Cenozoic*, by C. Wythe Cooke.

zone. These structures, although they in themselves are not of regional importance, are probably indicative of movements which in southwestern Alabama formed a downwarp influential in diverting the drainages which united to form the Alabama River.

The Hatchetigbee anticline and the Jackson fault may readily be post-Miocene structures since they involve the Catahoula formation, which, although it is early Miocene, is the latest Miocene deposit exposed in that portion of the state. It may be presumed that the Bethel fault is of the same age, although the formations which it effects are not so young. Since the Tombigbee maintained its course across the Hatchetigbee anticline, it is reasonable to suppose that the fold formed slowly. Its height if restored would be between 400 and 500 feet. Its altitude reaches 250 feet, and on it, near its highest part, are gravels such as are found in the Citronelle.

If the structures in southwestern Alabama were in the process of development as late as the Pliocene, it is possible that the general downwarp in that area may have been the cause of the diversion of the streams in the latitude of Montgomery and Selma and that this occurred at about the same time as the deposition of the high-level gravels on the outliers of Chunnenuggee Ridge.[1] After the diversion, the Alabama and Tombigbee rivers in their lower portions flowed in nearly parallel courses and probably were not united near the coast as they now are.

If the various events occurred in the order here outlined, they afford a consistent basis for the interpretation of the points under discussion. The deposition of the great quantity of sediments which constitute the Citronelle required a long time, and most of the formation may readily be conceded to be later than the initial diversion of the streams.

An alternative interpretation of the deformation of the Coastal Plain is that there was an upwarp affecting the southeastern part of the state. Some may recall that Veatch wrote: "The nature of

[1] The course of the Tombigbee River in Mississippi and near the western border of Alabama may be due to the diversion of southwestward-flowing streams. It lies on the easily eroded Cretaceous formations. The writer has seen only a portion of its valley and has not examined the divide to the southwest of the Tombigbee in Mississippi. It would be interesting to know whether there are gravels on it which may be of early Pliocene age.

the drainage together with certain geological facts suggests that the Chattahoochee River occupies the crest of a southward pitching anticline."[1]

In a text figure, he indicated the area of the anticline by a dotted line which includes the drainage of the Chattahoochee from Columbus, Georgia, to the confluence of the Flint River. In discussing the structure of the Coastal Plain, Stephenson in a recent article[2] has referred to the structure as a "broad upwarp," and shows an anticline in the position noted by Veatch. If the existence of such a structure could be proved, it might be appealed to as a contributing factor in explaining the peculiarities of the drainage, and the distribution of the high-level gravels in southern Alabama, but no one has adduced geologic facts that support the suggestion made by Veatch. Hager[3] reported what he called the Gordon anticline, extending across the Chattahoochee River from the southeast corner of Alabama into Georgia. There are some irregularities of dip on the river at the place noted, but not a well-defined structure. The writer has searched for structure along the Chattahoochee, both in Alabama and Georgia, and has contoured the structure of one key-bed crossing the river without finding evidence of an anticline such as Veatch suggested. A change in the general dip of the rocks of the Coastal Plain from southwest to south and then southeast takes place gradually in passing from west to east across Alabama over the buried axis of the Appalachians. If there is a broad upwarp in the Coastal Plain, affecting Alabama, it lies to the west of the Chattahoochee River.

At the close of Pliocene time, there was a moderate elevation of southern Alabama. As a result of this, the streams cut their channels deeper and terraces developed along them. The Alabama River and the Tombigbee removed the Citronelle where they flowed, and eventually united to form the Mobile River. Subsequent slight submergence has drowned the lower reaches of Mobile River and produced Mobile Bay. The waters of the Tombigbee and Alabama since

[1] Otto Veatch and Lloyd W. Stephenson, "Preliminary Report on the Geology of the Coastal Plain of Georgia," *Geol. Survey of Ga. Bull. 26* (1911), p. 63.

[2] *Op. cit.*, p. 294.

[3] Dorsey Hager, *Trans. A.I.M.E.*, Vol. LIX (1918), p. 430.

then have reached the coast through distributaries. These are now Mobile River and the Tensaw.

In conclusion: The suggestion is offered that at the end of the Miocene there was an emergence of the Coastal Plain of Alabama, and that streams flowed across the area in approximately parallel drainage lines. Downwarping of the southwestern part of Alabama in the early Pliocene caused diversions and captures of the streams in the latitude of Montgomery and Selma, and a lowland was developed on the Eutaw formation and the Selma chalk. The Alabama River, formed then, contributed coarse sediments to the deltaic deposits known as the Citronelle. The streams heading south of Chunnenuggee Ridge have established their southwestward courses since the downwarp in southwestern Alabama.

THE NATURE AND ORIGIN OF THE HORST AND GRABEN STRUCTURE OF SOUTHERN OREGON[1]

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ABSTRACT

In southern Oregon east of the Cascade Mountains a varied series of Tertiary lavas is cut by the northern continuation of the Basin Range faults, giving rise principally to relatively undissected horst and graben structure rather than to tilted fault-block mountains. The tensional origin of these faults is indicated by definite normal faulting, curving, and zigzag faults, step faults, circular fault basins, volcanic activity parallel to the faults, absence of folds, thrust faults, or other pressure effects, and by the even distribution of faults rather than their local concentration in zones of initial failure.

INTRODUCTION

In recent years the origin of fault blocks and of horst and graben structure has been the subject of considerable discussion. In the past these features were generally considered to be the product of normal faulting due to, or at least accompanied by, tensional stress, but in later years a compressional hypothesis, with various modifications, has won numerous supporters throughout the world.

In this country the Great Basin is the type locality for fault-block mountains, but, unfortunately, in much of this district the complexity of the pre-faulting structure and the relatively advanced state of post-faulting dissection have rendered the interpretation of the fault structures extremely difficult. In southern Oregon, however, at the northern end of the Great Basin, the faults, as they die out to the north, cut a series of undeformed Tertiary lavas, which overlie the older complex rocks. This simplification of the structure, coupled with the extreme youth of the desert erosion, makes the region ideal for a genetic and descriptive study of the faults.

During the past four summers the writers have devoted much time to the study of the volcanics exposed in the long fault scarps

[1] Presented in abstract at the Forty-first Meeting of the Geological Society of America (1928).

of this region. To avoid the repetition or omission of flows in the collecting of samples, it was necessary to work out the structure in considerable detail at the localities where sections were taken. Therefore much information has been accumulated regarding the structure of the region. This has been further supplemented by careful study of some of the more important ranges and by considerable work of a reconnaissance nature throughout the entire volcanic district. Although it will require several years of field work to elucidate the structural details, certain of the major features appear to the writers to be sufficiently definite to warrant some discussion of the regional problem.

PREVIOUS WORK

A general outline of the geology and structure of southern Oregon has long been available from the early reconnaissance reports of Russell[1] and the water-supply studies of Waring.[2] Davis[3] also contributed an important paper on this district, and Johnson[4] and Gilbert[5] have published on the faulting of the Klamath Lakes region.

In a recent paper dealing with the general geology and structure of southeastern Oregon, Warren Dupré Smith[6] advances an interpretation of the origin of the structural features of the district which differs radically from that of other workers in the field. He reaches

[1] I. C. Russell, "A Geological Reconnaissance in Southern Oregon," *U.S. Geol. Survey, Ann. Rept. 4* (1882–83), pp. 431–64; "Preliminary Report on the Artesian Basins in Southwestern Idaho and Southeastern Oregon," *U.S. Geol. Survey, W.S.P. 78* (1903); "Notes on the Geology of Southwestern Idaho and Southeastern Oregon," *U.S. Geol. Survey Bull. 217* (1903); "Preliminary Report on the Geology and Water Resources of Central Oregon," *U.S. Geol. Survey Bull. 252* (1905).

[2] Gerald A. Waring, "Geology and Water Resources of a Portion of South Central Oregon," *U.S. Geol. Survey, W.S.P. 220* (1908); "Geology and Water Resources of the Harney Basin Region, Oregon," *U.S. Geol. Survey, W.S.P. 231* (1909).

[3] W. M. Davis, "The Mountain Ranges of the Great Basin," *Bull. Mus. Comp. Zoöl.* (Harvard University). Vol. XLII, (1903–5, pp. 164–72; reprinted in *Geographical Essays.*

[4] D. W. Johnson, "Block Faulting in the Klamath Lakes Region," *Jour. of Geol.*, Vol. XXVI (1918), pp. 229–37.

[5] G. K. Gilbert, "Studies of Basin-Range Structure," *U.S. Geol. Survey Prof. Paper 153* (1928), pp. 76–86.

[6] "Contribution to the Geology of Southeastern Oregon (Steens and Pueblo Mountains)," *Jour. of Geol.*, Vol. XXXV (1927), pp. 421–41.

the conclusion that the fault-block mountains and accompanying grabens are due to thrust and not to normal faulting.

AREAL GEOLOGY AND STRATIGRAPHY

Southeastern Oregon lies in the northernmost part of the basin and range province. It is a broad, uneven plateau, 4,000–5,000 feet in elevation, diversified by north-south fault mountains. In the southern part of the state the fault scarps rise precipitously 2,000–5,000 feet above the surface of the adjoining playas, but as one follows them farther and farther to the north they gradually decrease in elevation until they die out in a relatively undeformed plateau. Faulting is still much in evidence on this plateau, but the throw of the faults, instead of being measured in thousands of feet, seldom exceeds a few hundred. The fault structure apparently ceases with the Blue Mountains–Ochoco Mountains uplift since in the Columbia River Plateau to the north faulting is comparatively unknown. In southern Oregon the larger topographic forms are due almost entirely to deformation; stream erosion has only begun to modify the surface features produced by faulting.

The compilation of even an approximately correct stratigraphic table of the formations of southern Oregon is still a problem of the future. It will suffice to say here that the area is characterized by great thicknesses of Tertiary lavas of various types. The main lava floods were of basalt, but there were also many flows of andesite, rhyolite, and dacite as well as extensive areas of tuffaceous deposits. Although older crystalline rocks are exposed at several localities, volcanics, excluding playa deposits and alluvium, make up at least 90 per cent of the surface rock in the area directly concerned in this paper.

The "Tentative Table of Stratigraphy" for this region given by Smith[1] is misleading to those unfamiliar with the district because of its failure to state adequately the basis on which the age assignments are made, and because of its numerous errors. Although Knowlton[2] placed the Trout Creek formation in the Eocene, Smith[3]

[1] *Ibid.*, p. 428.

[2] *U.S. Geol. Survey, W.S.P. 231*, p. 20.

[3] *Op. cit.*, p. 428.

definitely assigns these beds, as well as the tuffaceous deposits near Alvord Ranch, to the Lower Miocene[1] without mentioning any cause for the change in determination.

Along the Steens Mountain scarp the Alvord tuffs referred to above are cut by two great elongate vents: one of andesite and an older one of rhyolite. These beds were also covered by flows of andesitic and rhyolitic composition before the eruption of the great thickness of basalt, yet in Smith's table all pre-basaltic lavas are referred to the Eocene. According to this table, the Alvord tuffs are succeeded by the "Miocene" "Columbia lava." The assignment to the Miocene and the correlation with the Columbia River lava[2] is based on "their great thickness and their superficial resemblance to the Columbia lava, and the presence of the lower Miocene Trout Creek Formation."[3]

In a subsequent part of this paper it will be shown that the thickness of the lava series at this locality is considerably less than that assigned to it by the author of the table, and the evidence of the Trout Creek formation has already been discussed. Although in the opinion of the writers this series of thin-bedded, open-textured basaltic lavas shows no resemblance to the Miocene Columbia River series, with which they are familiar, Smith's age assignment may be approximately correct. The Steens Mountain basalt correlates directly with that of Pueblo Mountain which Merriam[4] found to be definitely older than the Thousand Creek beds of the Lower Pliocene and probably older than the Virgin Valley beds of the Upper Miocene.[5]

[1] Yet in his abstract Smith assigns these beds to the Oligocene.

[2] I. C. Russell first proposed the name "Columbia lava" for this series, but later changed it to "Columbia River lava" to avoid confusion with the Columbia formation of the Atlantic states (*U.S. Geol. Survey, W.S.P. 53*, p. 28).

[3] W. D. Smith, *op. cit.*, p. 427.

[4] J. C. Merriam, "Tertiary Mammal Beds at Virgin Valley and Thousand Creek in Northwestern Nevada," *Univ. Calif. Publ. Bull. Dept. Geol. Sci.*, Vol. VI (1910–11), pp. 21–53, 199–304.

[5] On the other hand, R. J. Russell, in an article that has appeared since this paper went to press, states the opinion that Merriam has confused the relations in the Thousand Creek district, owing to the intricacy of its faulting, and that the Pueblo and Steens basalts are really Pliocene in age and hence correlate with the Warner basalt in the Warner Range of California. ("Basin Range Structure and Stratigraphy of the

The "Pliocene" of the table is represented by basalt dikes which cut the lavas of Steens Mountain and by rhyolite "capping." Not only do the dikes show definite petrographic and textural correlation with the "Miocene" lava flows, both being composed of a somewhat anomalous type of basalt, but at one locality the actual point of extrusion is exposed and a dike can be seen passing into a lava flow. On the face of the mountain there are also vents of acidic lavas which are older than the basalt and some dikes of a more normal type of basalt, which may be younger. Not only does rhyolite occur as a "cap," but acidic lavas are interbedded with the basalt here as well as at a number of other localities in southern Oregon.

STRUCTURE

PRELIMINARY STATEMENT

Some of the best-defined fault mountains in the world occur in southern Oregon. The frowning colonnaded escarpments with relatively insignificant piles of débris at their bases emphasize both the recency of the faulting and the incompetency of stream erosion in this arid district. As examples of the remarkable preservation of the more ephemeral features associated with the faulting may be mentioned the presence of large slickensided surfaces on exposures of the acidic lavas cut by the Steens Mountain fault, and the occurrence of drag effects in the bedded lavas exposed on the fault scarps. Features of this sort are not abundant, however. On a number of the fault scarps stream erosion has made quite appreciable progress, although none of the ranges is dissected to the extent that characterizes the majority of those in Nevada.

Horst and graben structure is far more typical of southern Oregon than is true tilted fault-block structure (Fig. 1). The region is characterized by seven great north-south tectonic depressions or graben, bounded on either side by fault scarps. From west to east the major fault depressions are in order: the Klamath graben; the Summer Lake–Chewaucan Marsh–Goose Lake depression; the

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Warner Range, Northeastern California," *Univ. Calif. Publ. Bull. Dept. Geol. Sci.*, Vol. XVII (1928), pp. 416–17, 429.) It cannot be urged too strongly, however, that the correlation of basaltic series on the basis of lithologic similarity, or on their stratigraphic relationship to local masses of acidic lava, is very likely to lead to erroneous results.

Warner graben; the Guano graben; Catlow Valley, the Alvord graben, and the McDermitt Valley depression. Only the five tectonic depressions in Lake and Harney counties will be discussed.

THE SUMMER LAKE–CHEWAUCAN MARSH–GOOSE LAKE DEPRESSION

The valleys in which Summer Lake, Chewaucan Marsh, and Goose Lake lie form a somewhat disconnected depression occupying the central portion of a very wide, low, uparched area in the basaltic lavas.[1] The eastern margin of this composite depression is

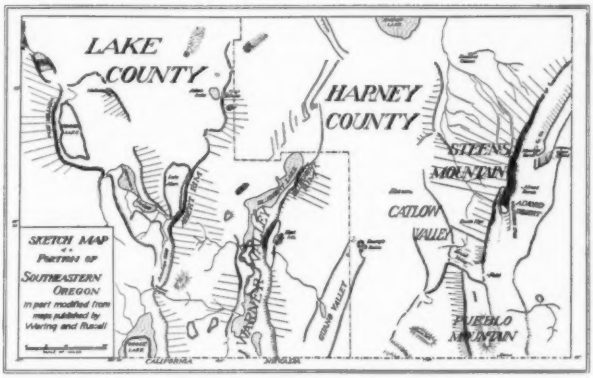

FIG. 1

bounded by the prominent fault scarp known as Abert Rim. Although decidedly zigzag in detail, the Abert Rim scarp forms a practically continuous westward-facing wall extending more than 80 miles in southern Oregon and continuing southward into California. In the southern part of the state it forms the eastern-bounding scarp of the Goose Lake graben. The main Goose Lake fault dies out a little north of Warner Canyon, but the zone of faulting is continued by a fault scarp which rises a few miles to the east, forming the eastern wall of Antelope Valley and continuing along the eastern shore of Lake Abert, where it rises abruptly more than 2,000 feet above the waters of the lake. A similar relationship exists farther to the north where the eastern margin of the level surface of the

[1] Gerald A. Waring, *U.S. Geol. Survey, W.S.P. 220*, p. 26.

Alkali playa comes to rest directly against the foot of the fault scarp without the development of an intermediate alluvial apron. Near Alkali Lake the fault line cuts squarely across a pre-faulting volcanic vent (Grays Butte).

Winter Rim, which overlooks Summer Lake from the west, presents many of the same details as Abert Rim, but the scarp, instead of being long, straight, and continuous, is a decided arc. The basal topography is diversified by a few landslides, but these features are negligible for such a steep escarpment. Near the southern end of Summer Lake an irregular mass of acidic lava marks the location of an old volcanic vent cut by the scarp. At this same point the scarp bends rather sharply from an approximate north-south direction to one trending roughly S. 65° E. Acidic tuffs underlie the basaltic lavas at many points along the scarp, and many springs arise near the fault.

Certain features connected with the Summer Lake depression are worthy of special mention. At its upper end Waring maps a continuous zone of faulting which runs in a half-circle about the northern end of the basin.[1] Throughout this entire zone the downthrow is toward the lake, but at Mount Diablo Pass, which lies on a continuation of this zone, the conditions are reversed. When followed to the south the Mount Diablo fault dies out, and some miles farther the fault defining the eastern margin of Chewaucan Marsh starts, but with the downthrow in a direction opposite to that of the Mount Diablo fault. This system of faults almost completely surrounds the Summer Lake depression, defining it as a roughly circular block which has been tilted to the west and at the same time differentially depressed in relation to the adjoining country (see Map, Fig. 1). This circular block has also been cut by a few minor faults.

The depression in which Silver Lake (now dry) lies appears to be of a similar nature. This basin forms the northwestern termination of the line of depressions of which Chewaucan Marsh and Summer Lake are an integral portion. Not only is Silver Lake bounded on the southwest and northeast by definite fault scarps, but it is also bounded on the southeast, if not by an actual fault, at least by a

[1] *Ibid.*, Plate VI; *U.S. Geol. Survey, W.S.P. 231*, Plate III.

distinct warp. Silver Lake thus occupies a horseshoe-shaped depression which opens northwestward into the wide expanse of Pauline Marsh.

Chewaucan Marsh is a true graben. Its eastern wall is formed by the fault scarp of the Chewaucan block, a true tilted fault block whose back slope is partially covered by Lake Abert. A long, thin step fault block extends for a considerable distance along the southern end of the Chewaucan fault scarp.

Goose Lake also lies in a true graben which continues southward into California.

THE WARNER GRABEN

Warner graben is similar to Goose Lake graben in that the lava flows in the high escarpments which confine the valley dip away at low angles on either side. In the southern part of the state it is a true graben bounded in many places by walls over 3,000 feet high. A few miles north of Plush the western wall disappears, possibly due to burial beneath a surficial covering, so that the northern part of the valley, except for its extreme end, lies between the high eastern scarp known as Bluejoint Rim and the tilted Abert block. Near the northern end of the graben the western fault again appears as a low scarp which truncates obliquely a series of tilted blocks formed by transverse faults that trend approximately north-south.

At Hart Mountain the eastern monoclinal block is cut by a fault which parallels the main scarp. The downthrow of this fault is to the east, and it thus defines this portion of the graben wall as an undissected horst only about 2 miles in width. Farther north, immediately east of the extensive playa that forms the final remnant of Bluejoint Lake, the eastern wall of the graben is formed by the high, practically undissected Bluejoint Rim scarp which rises precipitously from the lake bed with but an insignificant accumulation of talus at its base (Fig. 2). Continuing farther to the north this scarp curves slightly westward. Paralleling it, in the center of the graben, two fault blocks tilt to the southwest. To the west of these the curving scarp of a third somewhat similar block forms the eastern wall of another smaller graben which enters from the west at almost right angles. This graben, curving northward to N. 35° E., continues for at least 10 miles as a fault depression 1–2 miles wide, bounded by

continuous scarps several hundred feet in height. In part, the floor of this depression appears to be a typical playa basin, but a large part of it is composed of low rocky exposures which are locally defined by transverse faults. To the north it ends on the gently tilted dip-slope of a fault block, which is cut within a quarter of a mile by the western scarp of another graben. This third fault depression is, as a rule, about a mile in width. Defined by fault scarps 100 feet or

FIG. 2.—Aerial view looking northward along the 1,800 foot fault scarp forming Bluejoint Rim. The low curving scarp at the extreme northern end of the graben appears in the distance at the left. Note the landslides in the foregound.

more in height, it continues northward in a somewhat irregular course.

Near Hart Mountain several andesitic and basaltic vents are exposed on the scarp.

GUANO GRABEN

The Guano graben is considerably smaller than the other major grabens of southern Oregon. It appears to have been formed by the sinking of the central floor without marked concomitant elevation

of the bounding plateau. The surface of the plateau on the two sides of the graben and at its northern end is at an approximately uniform elevation. This plateau, in which the sunken trough lies, is not divided into tilted fault blocks, but is a relatively uniform mass.

To the west of the volcanic cone known as Beatty's Butte the western side of the Guano graben commences as a low scarp, to the

FIG. 3.—Aerial view of the extreme northern end of Guano graben. The western bounding scarp is just beginning at the extreme left. A number of low scarps facing uniformly southward can be seen trending almost at right angles to the graben wall. The dropping of the most southerly block (which occupies the left foreground of the picture) has caused the rejuvenation of the stream. Other irregular scarps are seen to the west of the canyon.

east of which a succession of small east-west fault scarps, with downthrows to the south, indicate that the graben is initiated by the differential sinking of several blocks which have been dropped to progressively greater depths, thus forming a series of broad steps leading down from the north (Fig. 3).

CATLOW VALLEY

Adjacent to Steens Mountain the eastern monoclinal block of Warner graben is covered by flat-lying sediments marking the lake

that formerly occupied Catlow Valley. On the east this valley is bounded by the prominent western scarp of Steens Mountain which begins at its northern end as a monoclinal warp and then breaks into a fault scarp that increases in elevation until it reaches a height of about 1,500 feet. The southern end of the valley is also defined on the west by a fault scarp that extends southeastward for approximately 15 miles. Opposite this scarp, on the east side of the basin, the southern continuation of the eastern fault curves through an arc of over

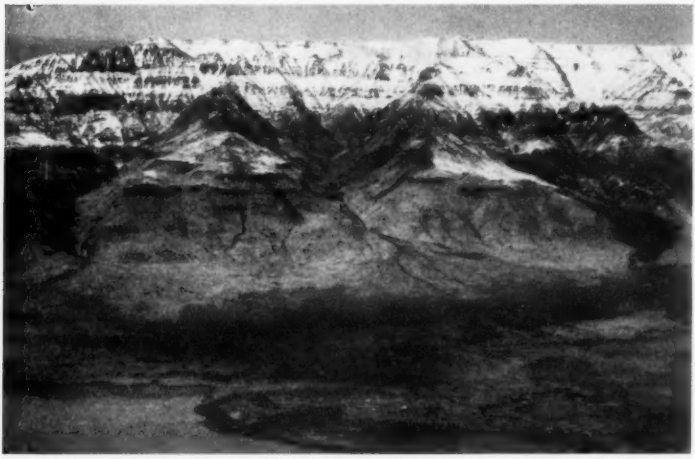

FIG. 4.—Aerial view of the high eastern scarp of Steens Mountain. At this locality the summit of the mountain rises approximately 5,400 feet above the playa shown in the left foreground.

100°, the southern end having an orientation of S. 70° W. This scarp gradually decreases in height from over 1,000 feet to about 400 feet before it is truncated by a transverse fault. To the south the topography is complicated by irregular exposures of acidic extrusives.

THE ALVORD GRABEN AND STEENS MOUNTAIN

Steens Mountain is by far the most magnificent fault mountain in southern Oregon. Its eastern escarpment, towering in a series of precipitous cliffs and slopes over 5,400 feet above the floor of the adjacent Alvord graben (Fig. 4), is a spectacular contrast to the

long, gentle dip-slope which forms the western ascent to the mountain's summit. Since its eastern escarpment affords the best exposures and the best vertical section of lavas of any escarpment in southern Oregon, the writers have spent a large amount of their time in a study of its structure and volcanic succession. The results of this study are decidedly at variance with Smith's idea that this mountain and the adjacent Alvord graben owe their origin to thrust and not to normal faulting.

Stratigraphy.—Smith states that on "the eastern escarpment, where nearly 5,000 feet of rocks are exposed, the complete stratigraphy of this mountain can be made out almost at a glance,"[1] and then gives approximately the data first recorded by Russell in 1903, namely, that the mountain consists of 1,000 feet of tuffs overlaid by 4,000 feet of basalt.[2] The present writers, however, found the stratigraphy of the mountain to be decidedly complex and variable throughout its entire extent.

The base of the tuffaceous series is not exposed, but from the existing evidence its thickness has been greatly exaggerated, in part probably due to its repetition by step faulting. Directly to the north of Wildhorse Spur a rhyolitic vent paralleling the scarp near the fault line cuts these beds and wells into a thick flow. This flow is overlaid by bedded tuffs containing small basic sills. These upper tuffs, which are about 200 feet thick, are in turn capped by a 300-foot dacite flow. On top of this another even thicker flow of dacite has welled from a vent which lies directly north of the center of the Wildhorse Spur. Southwest of the Alvord Ranch, low on the scarp, the rhyolitic vent and the overlying dacitic series have been cut by the southern end of a great elongate andesitic vent (Fig. 5) which parallels the scarp for another 10 miles. This vent, cross-sectioned by the deep valleys on the face of the escarpment, is finally truncated and concealed by a transverse fault about a mile south of Mann Lake Ranch.

These acidic lavas and vent fillings, which form the principal exposures through a vertical range of about 2,000 feet, are overlaid, apparently conformably, by a series of flows of olivine basalt which

[1] *Op. cit.*, p. 430.

[2] *U.S. Geol. Survey Bull. 217*, pp. 15–16.

is characterized by its open texture and abundant phenocrysts of labradorite. The exposed thickness of these basalts is close to 3,000 feet. Their base, however, overlies either the acidic vents or the thick accumulations of their extruded lava, which in either case undoubtedly formed topographic eminences at the time of the basaltic extrusion.

FIG. 5.—Curving columnar jointing at the margin of the andesitic vent on Steens Mountain.

The genetic relationship of the basalt dikes on the face of the mountain to the lava series has already been discussed. Probably contemporaneously with their intrusion injections of a similar lava formed the thin sills in the bedded tuffs at the base of the mountain.

Although Smith definitely attributes the steplike profile of Steens Mountain to slumping due to the presence of the tuffs at the base of the series,[1] detailed examination reveals that the irregularities are due to the presence of the acidic vents which parallel the face of the mountain, to the severeness of the glacial erosion on the upper part of the escarpment, and to distributive faulting.

Structure.—In the opinion of the present writers, Steens Mountain and Pueblo Mountain form a structural unit[2] due to tensional faulting. In this they agree with the earlier work of Russell, Davis, and Waring.

Although the previous work covers the general topographic features, certain points need emphasis. The most important of these is the scarp which forms the western margin of southern and central Steens and continues southward as the northwestern border of the Pueblo Mountain block. This scarp has been previously described as forming the eastern boundary of Catlow Valley. In 1902 Davis did not visit the western side of the mountain, but from an advantageous view of the even escarpment, he considers in his admirable report that "the southern and middle parts of the Stein [Steens] Mountains are carved in what seems to be an uplifted block with a fault along the western as well as the eastern border."[3]

Waring maps a well-defined escarpment on the western side of central and southern Steens continuing south to Pueblo Mountain. At Broad Valley this scarp dies down to a little over 200 feet, but both to the north and to the south it is 1,000 feet or more in height. Owing to the absence of the customary hot springs and to the fact that the block dipped toward the escarpment rather than away from it, he did not draw in a fault line.

Smith does not even mention this scarp in his discussion of the district despite his statement that he has "completed the topographic sketch of the mountain [Pueblo] left blank by Waring."[4] In this blank portion of Waring's map the scarp is nearly 1,000 feet in height (Fig. 6).

Well-developed drag is exposed on the scarp in a locality east of Blitzen, testifying to its origin as a fault rather than as an erosional

[1] *Op. cit.*, p. 430.
[2] Cf., *ibid.*, pp. 437–40.
[3] Davis, *op. cit.*, p. 167.
[4] *Op. cit.*, p. 438.

feature. This fault, facing a recent lake basin, decreases in throw and gradually dies about 20 miles north of Broad Valley.

This valley, which separates Steens from Pueblo Mountain, was produced by faulting in a northwesterly direction. The eastern end of the valley is covered to a depth of at least 400 feet by sediments eroded from the adjacent country. With north-south faulting, or a

FIG. 6.—Aerial view of the western scarp of Pueblo Mountain (looking south). A part of Broad Valley is shown in the foreground at the left. Catlow Valley on the right.

continuation of it, the block on which the sediments rest was tilted to the west at an angle of about 5°, raising the eastern end about 400 feet or more. These soft, easily eroded deposits, still retaining a distinct eastern escarpment, extend westward for several miles from Field, a postoffice at the junction of the Denio and Broad Valley roads. The conglomeratic facies of the sediments contain blocks of the predominant types of lava on the mountain, especially of the characteristic basalt.

In the southern part of Steens Mountain the dip of the basalts to the west increases and closely corresponds to the inclination of the

basalts south of Broad Valley. Except for the previously mentioned transverse fault zone, the Steens-Pueblo Range, defined on each side by a common fault scarp, appears to the writers to form a unit—a tilted horst gradually increasing in westward dip as its southern end is approached (Fig. 7).

East of the high central mass of Steens Mountain, near the Alvord Ranch, 10 miles of the recent lake bottom, forming the Alvord

FIG. 7.—Aerial view to the southward from above the extreme southern end of Steens Mountain. Southern Steens occupies the foregound, the down-dropped Broad Valley region appears in the middle distance, and Pueblo Mountain rises still farther in the distance. The structural continuity of Steens Mountain and Pueblo Mountain is apparent.

Desert, stretch between the two escarpments which bound the graben. The eastern escarpment, which truncates the east limb of the hypothetical anticline,[1] rises only a few hundred feet above the

[1] Professor Smith emphasizes his contention that Steens Mountain and the low scarps to the east of Alvord Desert resemble a faulted arch by neglecting to mention a vertical exaggeration of approximately 10 to 1 in his block diagram. The reader should also not be misled by his Fig. 5 in which the profiles of Steens Mountain and Abert Rim are drawn with one single line as if they were actually connected, mutually facing escarpments. Abert Rim is over 80 miles to the west of Steens Mountain (see map, Fig. 1).

sand dunes. The exposures of this scarp, however, dip predominately to the southeast rather than normal to the scarp. The northern part of the valley between the two fault scarps contains numerous irregular tilted fault blocks of various size, some of which rise a thousand feet or more above the playas.

About 8 miles east of Mann Lake a marked curve in the eastern escarpment forms the eastern wall of a small, oval-shaped playa

FIG. 8.—Aerial view, looking eastward across the Upper Alvord playa. Note the prominent step fault on the eastern scarp of the basin.

basin about 3 miles long and 2 miles wide. This depression is completely bounded by a continuous series of fault scarps which locally reach a height of more than 1,000 feet (Figs. 8 and 9). Along part of the fault line water rises to the surface so that this small basin is bordered by a semicircle of flowing springs. On a small scale it resembles the Summer Lake depression, but differs from that feature in that it has sunk without apparent tilting and so is surrounded by continuous scarps with the downthrow toward the basin on all sides. These circular depressions, surrounded by fault scarps, appear to be a common product of the forces which were responsible for the horst and graben structure of southern Oregon.

It should be emphasized that step faulting is characteristic of the scarps associated with Steens Mountain and the Alvord graben (Figs. 8, 9, and 10). The step blocks are commonly quite narrow, but they have considerable longitudinal extent. The lavas within the step blocks usually have approximately the same strike and dip as the lavas in the main block, and consequently when the escarpment is viewed from the playa below, no marked evidence of minor

FIG. 9.—Aerial view looking northward into the northern end of the Alvord graben. The Upper Alvord playa occupies the central part of the picture. Beyond, the tops of a series of tilted fault blocks rise above the floor of the Alvord Basin, and in the distance lies the eastern scarp of northern Steens. Note the step fault on the Steens scarp.

faulting is discernible. In addition to the step faults there are transverse faults such as the one in Broad Valley and the one at Mann Lake already mentioned. There are some other subsidiary faults of a more complex type.

A CONSIDERATION OF THE COMPRESSIONAL HYPOTHESIS

With this brief outline of the structural features of southeastern Oregon in mind, we may turn to a consideration of the nature of the forces responsible for the structure.

W. D. Smith is not the first to suggest that the mountain ranges

of the Great Basin are due to compression. C. L. Baker[1] and W. H. Hobbs[2] have held similar, although not necessarily identical, views, and C. R. Keyes has at times emphasized the importance of thrust faults in this district. Thrusting has also been appealed to in explanation of various well-known grabens in other parts of the world.

Strong general evidence against the possible compressional origin of grabens has recently been advanced by Stephen Taber.[3] Many of

FIG. 10.—Showing the displacement of the lower dacitic flow north of Wildhorse Spur by step faulting. The two prominent layers are parts of the same flow.

his criteria are directly applicable to the region under discussion and can be substantiated by much additional testimony, both of a general and local nature. The writers consider the compressional hypothesis totally inadequate to account for the horst and graben structure of southern Oregon, and offer the following factors in confirmation of this viewpoint.

[1] "The Nature of the Later Deformation in Certain Ranges of the Great Basin," *Jour. of Geol.*, Vol. XXI (1913), pp. 273–79.

[2] *Earth Evolution and Its Facial Expression* (New York, 1921), pp. 105–7, 177.

[3] "Fault Troughs," *Jour. of Geol.*, Vol. XXXV (1927), pp. 577–606.

NORMAL FAULTING

1. Definite normal faults of large displacement have been found[1] by the writers at a number of localities, but no thrust faults have yet been discovered in this portion of southern Oregon.

On Steens Mountain a number of step faults occur on the face of the escarpment close to the position of the main fault. The actual fault planes are best exposed where the fault zone cuts the resistant acidic lavas and vents to the north of Wildhorse Spur. Here a series

FIG. 11.—A slickensided surface on one of the step faults cutting the dacite

of faults, with slickensided surfaces (Fig. 11) still preserved on the scarps, have permitted normal displacement of nearly 1,000 feet in three major fractures (Fig. 10) and numerous minor ones. The irregularities of the striations on the planes, which dip at about 60°, testify to normal movement. Additional testimony is offered by the displacement of the basic sills in the interbedded tuffs.

Farther to the west in the deep glacial cirques additional normal faults occur. Some of these, however, dip westward instead of toward the adjacent playa basin. In one instance the intersection of two faults, one dipping toward the west and the other toward the

[1] Cf. W. D. Smith, *op. cit.*, p. 436.

east, has permitted the dropping of a wedge-shaped block. The maximum displacement observed on the westward-dipping faults is only 100 to 200 feet. Proof of the direction of movement is offered by the displacement of basaltic dikes (Fig. 12) and of a thin bed of tuff interstratified near the base of the basaltic series.

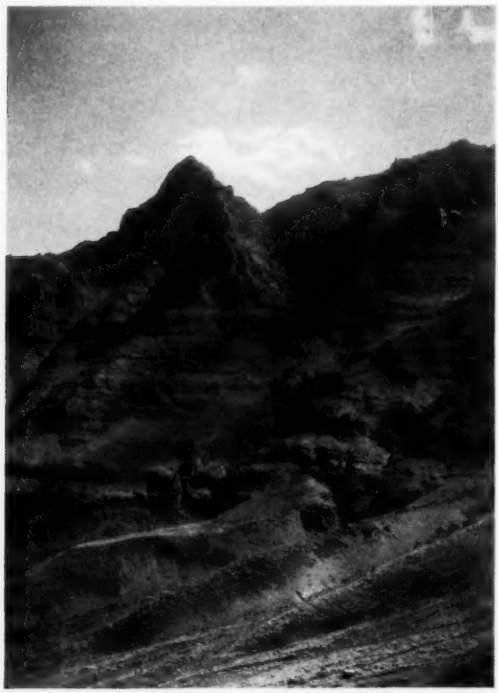

FIG. 12.—Looking south across the head of a cirque west of Alvord Ranch. The ravine in the center of the picture follows a normal fault dipping westward. The offset of the dike cutting the basaltic series indicates the normal displacement.

The observed subsidiary faults invariably dip at angles of 60° or more. Many of the fault surfaces can be traced through a vertical range of 1,000 feet without showing any tendency to flatten. No instance has ever been observed in which the block showed reverse rotation. These features, together with the fact that the faults are

genetically associated with other normal faults which dip away from the playa, as shown by the depression of wedge-shaped blocks where faults of the two systems intersect, furnish positive evidence that these faults were not produced by superficial landslides. Many landslides can be found on Steens Mountain, but they differ radically from the step fault blocks in topography and genesis. The landslip blocks invariably show the characteristic reverse rotation resulting in the usual hummocky surfaces and irregular depressions between the landslip masses and the adjacent scarps. West of Alvord Ranch occur landslip depressions occupied by small lakes. The landslip blocks never have the remarkable longitudinal extent which characterizes the step blocks.

Although the actual fault planes are not exposed, step faulting is apparent from physiographic evidence on the east side of upper Alvord Basin (Fig. 8), on the east side of northern Steens (Fig. 9), on the Catlow Valley scarp south of Broad Valley, and on the face of the Chewaucan block. At numerous other localities the physiography strongly suggests step faulting.

GENETIC IMPORTANCE OF STEP FAULTS

2. The writers are of the opinion that the numerous step faults defining narrow step blocks which extend for a considerable distance along the fault scarps of southern Oregon are a direct proof of normal faulting and are inexplicable by the compressional hypothesis. Some advocates of the compressional hypothesis have explained these features as superficial phenomena consequent on the overhang produced by the emergence of a thrust along a valley side. A diagrammatic representation of this idea given by E. J. Wayland in his account of the Albertine Rift is[1] reproduced by Smith[2] in his paper on Steens Mountain, and has even been reproduced and the explanation quoted with approval in a standard textbook of structural geology.[3] Therefore it may be worth while to digress for a moment in order to point out some very obvious fallacies which it contains. The dia-

[1] "Some Account of the Geology of the Lake Albert Rift Valley" *Geog. Jour.* Vol. LVIII (1921), p. 353.

[2] *Op. cit.*, p. 434, Fig. 8.

[3] Bailey Willis, *Geologic Structures*, p. 81, Fig. 57.

gram in question is reproduced as Figure 13. In the sketch of the scarp due to thrusting, the overhanging portion of the emerged block is assumed to have fallen as two narrow step blocks so that a result is achieved very similar to the escarpment produced by normal faulting. These step blocks are, then, according to Wayland's hypothesis, nothing more than landslides. No explanation is offered as to the failure of these blocks to show the characteristic reverse rotation[1] of ordinary landslides. Wayland states that movement on a thrust of this type could only be initiated by "enormous pressure" and that "tremendous reliefs" are necessitated in satisfaction of this pressure.[2]

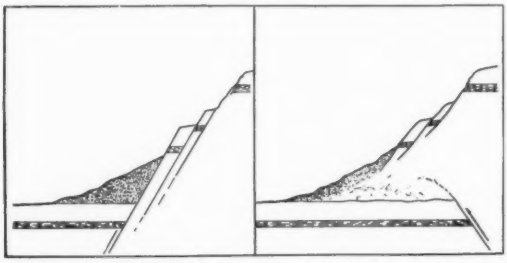

FIG. 13.—Wayland's diagram showing the similarity of thrust and normal fault scarps. The step faults on the thrust scarp are regarded as superficial landslides.

A natural consequence of this pressure would be the extreme shearing, crushing, and granulation of the rocks adjacent to the thrust surface. When this crushed mass emerged overhanging the valley, one would expect it to give way and fall in an indiscriminate jumble of débris. No large blocks arranged in an orderly step-like fashion such as Wayland has drawn would be expected, and their occurrence could only be regarded as fortuitous. That blocks of this type could extend unbroken for long distances along the face of the escarpment is inconceivable.

It is characteristic, however, that the narrow blocks bounded by step faults commonly extend for distances of a mile or occasion-

[1] I. C. Russell, "Geology of the Cascade Mountains in Northern Washington," *U.S. Geol. Survey, Ann. Rept. 20* (1900), Part II, p. 194; "Topographic Features Due to Landslides," *Pop. Sci. Mo.*, Vol. LIII (1898), pp. 480–89; Bailey Willis, *op. cit.*, p. 44; C. K. Leith, *Structural Geology* (New York, 1923), pp. 202, 203–4.

[2] *Op. cit.*, p. 357.

ally several miles without marked disruption.[1] Obviously the faults which bound them extend down parallel, or approximately parallel, to the main fault along which the maximum displacement of the range occurred and are not surficial features that stop at the valley floor.

However, let us grant for the moment that step faults might be formed as assumed by Wayland, and inquire into the possibility that the lower blocks would still preserve their steplike relationship to those higher up on the escarpment. The diagrammatic sections in Figure 14 convey the writers' impressions of the necessary result.

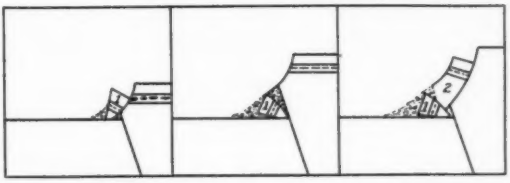

FIG. 14.—Supposed stages in the evolution of a thrust fault scarp, provided step blocks actually do form. On slight emergence the tip of the thrust block would slip off, forming step block *1*. Further movement would overturn and override this block. If a second step block, *2*, is formed it will no longer have a steplike relationship to the first block. Compare with Fig. 15.

Upon a relatively small emergence of the thrust block, the first step, *1*, would form, further thrusting would overturn this block, and its lower part would be overridden by the advancing mass. The second step block, *2*, therefore would not have a steplike rela-

[1] F. Dixey, "The Nyasaland Section of the Great Rift Valley," *Geog. Jour.*, Vol. LXVIII (1926), pp. 120, 124–25; J. W. Gregory, "The African Rift Valleys," *ibid.*, Vol. LVI (1920), p. 23; Douglas W. Johnson, "Block Mountains in New Mexico," *Jour. of Geol.*, Vol. XXXI (1903), pp. 136–37; Waldemar Lindgren, "The Tertiary Gravels of the Sierra Nevada," *U.S. Geol. Survey, Prof. Paper 73* (1911), p. 42; G. D. Louderback, "The Basin Range Structure of the Humbolt Region," *Bull. Geol. Soc. Amer.*, Vol. XV (1904), pp. 324, 334, 341–42; Morphologic Features of the Basin Range Displacements in the Great Basin," *Univ. Calif. Publ. Bull. Dept. Geol. Sci.*, Vol. XVI (1926), No. 1, pp. 1–31; John Parkinson, "The Great African Troughs in the Neighborhood of the Soda Lakes," *Geog. Jour.*, Vol. XLIV (1914), pp. 33–49; John A. Reid, "The Geomorphogeny of the Sierra Nevada Northeast of Lake Tahoe," *Univ. Calif. Publ. Bull. Dept. Geol. Sci.*, Vol. VI (1911), pp. 115, 117, 135–36; H. L. Sikes, "The Structure of the Eastern Flank of the Rift Valley near Nairobi," *Geog. Jour.*, Vol. LXVIII (1926), pp. 386, 389–90, 401.

tionship to the first, and this train of events would be continued as long as thrusting took place. The only way in which the relationship pictured by Wayland could occur would be to have the block thrust up unbroken to a position actually overhanging the valley (Fig. 15), then to have step block *2* form and this later split asunder and the outermost part dropped to form step block *1*. The difficulties that such a hypothesis must encounter to explain a number of parallel step blocks extending unbroken for a considerable distance along a high fault scarp are too obvious to merit discussion.

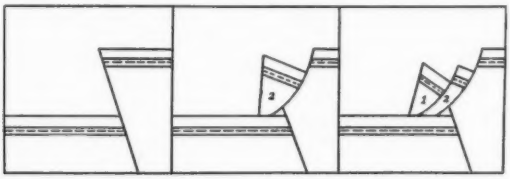

FIG. 15.—Stages in the evolution of a thrust fault scarp according to Wayland's diagram (Fig. 13). The entire block must first be shoved up to a position overhanging the valley, then step block *2* must slide down and later break and the outer portion of it slip down to form step block *1*. Such a mechanism appears to be very improbable. Compare with Fig. 14. (Talus omitted from diagram.)

A necessary corollary to Wayland's method for the formation of step faults is that these faults are confined entirely to the main rift scarp and are not found on the back of the rift blocks or on the floor of the valley below. This is entirely out of accord with the evidence from southern Oregon, where subsidiary faults parallel to the main fault escarpment can be found, not only on the back of the blocks, but also on the floors of the grabens.

We have yet to consider the possibility of step faulting in connection with upthrusts of the type postulated by Willis.[1] In the upthrust the fault emerges vertically at the surface, but flattens downward beneath the upthrust block. If a number of closely spaced upthrust surfaces formed a fault zone along which movement occurred, it would appear that a step-fault arrangement might be possible. As Willis carefully points out, however, any rotation of one block against another along a curved upthrust surface can only take

[1] *Op. cit.*, pp. 45–46, 78–82.

place by adjustment in the upthrust block, or else in the material immediately in front of the upthrust block. "Faults of this type are always accompanied by shearing, crushing and folding because the fault surfaces are not smooth uniform curves."[1] It would be natural to assume that in the case of a number of closely spaced upthrusts this adjustment, due to differential rotation along the upthrust surfaces, would find relief in disrupting the thin steps and toppling them forward into the graben. Locally, very wide portions of step blocks may possibly survive the tremendous pressure tending to disrupt them, but the effects of this pressure should certainly be apparent in the rocks composing them. Thin step blocks with considerable longitudinal extent could not remain unbroken. Willis clearly realizes that narrow step fault blocks cannot be formed in this way for in his paper on the Dead Sea Valley he appeals to the landslip idea in explanation of features of this type.[2]

The general conclusion is reached, therefore, that the narrow well-defined step blocks of considerable longitudinal extent which are a common feature of normal fault scarps are not to be confused with the irregular landslides and heterogeneous masses of débris that accumulate at the base of scarps produced by steeply dipping thrusts.

VOLCANIC VENTS ASSOCIATED WITH THE SCARPS

3. The prevalence of volcanic vents along the graben escarpments of southern Oregon is considered by the writers to favor the idea of normal rather than thrust faulting. There is clear evidence that vents with a linear arrangement along the fault zone have preceded, attended, and followed the main epoch of faulting. In particular, at Steens Mountain the presence of the large rhyolitic, dacitic, and andesitic vents as well as the numerous basaltic dikes, all with a predominant orientation parallel to a potential fault which later cut them, suggests that they occupied a line of tensional weakness even before the actual faulting had begun. Compression would close the fault fractures tightly and make them very unfavorable *loci* for vulcanism. In fact, some authors have stated as a general principle

[1] *Ibid.*, p. 46.

[2] Bailey Willis, "Dead Sea Problem: Rift Valley or Ramp Valley?" *Bull. Geol. Soc. Amer.*, Vol. XXXIX (1928), p. 513.

the theorem that magmas characteristically shun the thrust planes and tend to work inward toward the central portion of the deformed belt.[1] Where magmas have been intruded into areas undergoing severe compression they usually form concordant bodies parallel to the schistosity, or bedding, and not the roughly discordant types that are characteristic of volcanic feeders.

Although some authors have considered the presence of volcanic vents to favor the compressional hypothesis, the occurrence of these features along definite thrust planes has been very rarely recorded. Their common association with normal faults, however, is now well established, and numerous examples are forthcoming from widely separated parts of the world.[2] If we grant that the so-called "normal faults" are really thrusts we are at a loss to explain their common association with volcanic feeders, since in ordinary thrusts these are usually absent. On the other hand, if the normal faults are tensional this association is entirely logical.

CIRCULAR FAULT BASIN

4. If the roughly elliptical to circular depressions, exemplified by Summer Lake, Silver Lake, and the Upper Alvord playa, are due to compressional faulting, then the forces must have acted centripitally like the closing of a camera shutter. Seemingly a dome would have been the more logical structure under these conditions. It is particularly difficult to understand how, in the case of the Upper Alvord playa, the deformation could have been restricted to a very small central area only about 3 miles in diameter and yet was sufficiently severe to result in the walls of this tiny basin being thrust up as much as 1,000 feet above the playa surface. The actual

[1] Rollin T. Chamberlin and T. A. Link, "The Theory of Laterally Spreading Batholiths," *Jour. of Geol.*, Vol. XXXV (1927), p. 347.

[2] A. R. Andrew and T. E. G. Bailey, "The Geology of Nyasaland," *Quar. Jour. Geol. Soc.*, Vol. LXVI (1910), p. 235; G. L. Collie, "Plateau of British East Africa," *Bull. Geol. Soc. Amer.*, Vol. XXIII (1912), p. 313; J. W. Gregory, *The African Rift Valleys*, pp. 16, 20, 23, 28, 29, 33, 36; D. W. Johnson, "Block Faulting in the Klamath Lakes Region," *Jour. of Geol.*, Vol. XXVI (1918), p. 229; G. D. Louderback, *op. cit.*, p. 312; G. R. Mansfield, *U.S. Geol. Survey, Prof. Paper 153*, pp. 128, 135, 379, 390; John Parkinson, *op. cit.*, p. 36; H. L. Sikes, *op. cit.*, p. 388; E. O. Theile, "Further Notes on the Physiography of Portuguese East Africa, between the Zambezi River and the Sabi River," *Geog. Jour.*, Vol. XLVI (1915), p. 279.

mechanism of the formation of features of this type is somewhat obscure, but regional tension allowing the release necessary for movement of such small units appears to be absolutely essential.

ABSENCE OF FOLDING

5. Where steeply dipping thrusts have been found, the rocks associated with them are practically always buckled and folded. Smith placed much emphasis upon his own statements that the fault blocks in southern Oregon are "folded, tilted, and warped" and that "practically nowhere in this region do we see simple homoclinal blocks."[1] Field studies by the present writers do not bear out these statements as a general description of the regional structure. The statements apparently were based upon observations at the following three localities. One is a dome-shaped anticline with a northwesterly axis, which, according to Waring, has a 3° dip to the northeast and a westward dip of 2°–5°. This anticline, which is only about 5 miles long, lies fully 20 miles west of the northern end of the Steens escarpment. In the opinion of the writers it is probably due to local tensional deformation which is not sufficiently extreme to result in actual faulting. In addition, the structure has been complicated by late Pleistocene vulcanism at the adjacent Diamond Craters.

Catlow Valley, which forms the second locality, can be described as a "sag"[2] only at its extreme northern end. Farther to the south it is a dry lake basin defined by the western fault scarp of Steens on the east and a gently tilted block to the west upon which the lake sediments lie. Still farther south this western block is cut by a fault which converges toward the curving eastern scarp of the basin, thus defining the valley as a roughly V-shaped graben opening outward to the north.

The reverse dip of 20° to the east observed in Wildhorse Canyon about 5 miles from the summit forms the third structural irregularity commented upon.[3] Smith,[4] however, admits that this canyon appears to follow a fault line[5] separating a long fault splinter, known as the Wildhorse Spur, from the main mass of the mountain. This

[1] *Op. cit.*, p. 426.
[2] *Ibid.*
[3] *Ibid.*, p. 433.
[4] *Ibid.*, p. 428.
[5] *U.S. Geol. Survey, W.S.P. 231*, pp. 24–25, Plate III.

local sharp change in dip appears to the writers to be due to drag adjacent to the fault plane, and this opinion is further substantiated by Smith's statement that the dip is in the opposite direction lower down on the escarpment.[1]

Contrary to his statement on the characteristically "folded" blocks, Smith, in describing the western slope of Steens Mountain, testifies to the "long westward gentle dip slope, so gentle that in the region of Smith's Flat and so little affected by erosion that one can

FIG. 16.—Aerial view of the back-slope of the tilted Steens Mountain block (looking south).

gallop a horse over it at will."[2] The present writers have been much impressed by the fact that the back slopes of the tilted blocks are astonishingly simple in structure (Fig. 16). The average dip of the lavas in the central and northern portion of the Steens block, as shown by the symbols on Waring's map,[3] is about 3°. The mountain is 5,400 feet high and about 25 miles wide. Assuming that it is formed by simple tilting of horizontal beds, the calculated dip should be 2° 20′. The fact that the volcanic feeders

[1] *Op. cit.*, p. 433.

[2] *Ibid.*, pp. 427–28.

[3] *U.S. Geol. Survey, W.S.P. 231*, Plate III.

were located along the line which later marked the fault may indicate that even the slight discrepancy between the observed and theoretical dip is in part due to a primary tilt away from the vents which furnished the gradient necessary for flowage.

Similar conditions are found in connection with the other fault blocks, the majority of them being even simpler in structure than Steens Mountain. It is quite apparent that these blocks are far from accurately described when they are said to be "folded, tilted, and warped." On the other hand, they emphasize the total absence of severe compressional deformation in southern Oregon.

ABSENCE OF OTHER COMPRESSIONAL EFFECTS

6. In thrust faulting the overriding block, and to a lesser extent the overridden block, are generally much brecciated, crushed, and contorted adjacent to the thrust plane. Often the presence of a thrust may be inferred without reasonable doubt from these subsidiary features even though the actual fault surface is covered. Minor thrusts of small displacement are common features of the overthrust block.

None of these features can be found on the southern Oregon escarpments. In the hundreds of thin sections that have been prepared from lava samples collected on the face of the fault scarps no evidence of granulation or crushing can be detected. In the previously mentioned rhyolitic vent of the Steens escarpment, vertical open bands of lithophysae have retained their most delicate structures intact, and the highly incompetent waterlaid tuffs at the base of the mountain still retain their bedding undistorted. Both are in a position where they would have suffered the maximum amount of brecciation if the faulting were due to compression.

EVEN DISTRIBUTION OF THE DEFORMATION

7. Certain more general features of the southern Oregon fault-block country have no obvious explanation if we assume that these structures are due to compression. From west to east across the faulted portion of the state is a distance of more than 200 miles, and we have no indication that the fault structure ceases short of the areas that Mansfield has mapped in southeastern Idaho—a total distance of over 500 miles. In southern Oregon there are seven well-

defined north-south fault depressions of about equal magnitude. It would require a rather unusual distribution of stress, if we assume compression, in order to produce such uniform structures as these. Compressional stress generally tends to localize the failure in narrow zones, but in this district the failure is practically uniform over the entire area.

EFFECTS OF COMPRESSIONAL DEFORMATION IN THE COLUMBIA RIVER PLATEAU

8. Comparison with adjoining districts shows that there is no reason why the basalts of southern Oregon should not fold if subjected to compression. To the north the compression of the Columbia River basalt appears invariably to have resulted in folds[1] rather than faults. That the deformation in this region was severe is testified by the overturning of the anticlines at several localities.[2] Relatively, these anticlines are a very different type of structural feature from that commonly observed in southern Oregon. Rising as long narrow ridges of from 1,000 to 3,000 feet in height and from 2 to 12 miles in width, they are striking contrast to the anticlines of southern Oregon (if we assume that the grabens represent the sunken keystones of anticlinal arches). These anticlines would be from 25 to 50 miles in width and would probably average around 4,000 feet in height. Since the anticlines to the north are only partially dissected they probably were formed at approximately the same time as the fault features of southern Oregon. The anticlinal axes to the north trend from east-west to northwest-southeast, while the fault mountains of southern Oregon have a predominant north-south or northeast-southwest orientation.

[1] George Otis Smith, "Anticlinal Ridges in Central Washington," *Jour. of Geol.*, Vol. XI (1903), pp. 167–77; "Geology and Physiography of Central Washington," *U.S. Geol. Survey, Prof. Paper 19* (1903), pp. 1–40; Bailey Willis, "Physiography and Deformation of the Wenatchee-Chelan District, Cascade Range," *ibid.*, pp. 41–102; Gerald A. Waring, "Geology and Water Resources in South-Central Washington," *U.S. Geol. Survey, W.S.P. 316* (1913), pp. 22–25; Frank C. Calkins, "Geology and Water Resources of a Portion of East-Central Washington," *U.S. Geol. Survey, W.S.P. 118* (1905), pp. 40–44; J Harlen Bretz, "The Spokane Flood beyond the Channeled Scablands," *Jour. of Geol.*, Vol. XXXIII (1925), pp. 236, 242, 243, 249; J. P. Buwalda, by verbal communication, testifies to the folding of the basalt in the John Day region of north-central Oregon (see also *Bull. Geol. Soc. Amer.*, Vol. XXXIX [1928], p. 270).

[2] G. O. Smith, *op. cit.*

SMITH'S EVIDENCE IN FAVOR OF THE COMPRESSIONAL HYPOTHESIS

Smith's contention that such a pronounced topographic feature as Steens Mountain owes its 5,400 feet of height above the adjacent Alvord Valley to movement along a steeply dipping thrust that forced the walls of the graben up past the central portion "which did not drop down, but remained practically stationary at its original elevation,"[1] appears to the writers wholly unsubstantiated.

In support of this theory Smith cites certain experimental work in which graben-like structures have been produced by the compression of synthetic strata and of wooden beams. In the experiment by Jaggar,[2] however, folding rather than faulting was the dominant type of deformation. In addition, the stratigraphic succession of synthetic beds used in the experiment can hardly be expected to correspond to the volcanics of Steens Mountain in its method of yielding. As shown on the eastern margin of the Pueblo Range, the main Steens-Pueblo fault cuts directly downward into the crystalline basement beneath the volcanics instead of flattening and dying out in an incompetent bed as in the experiment.

The experiment which Smith cites and illustrates from Emmons' textbook is misquoted.[3] Concerning McAlister's experiment on the compression of a beam of firwood, Smith states: "It will be noted in the experiment that the shear approximates 45° in both sections. On Waring's map the great faults, such as Steens and Warner mountains, show a decidedly northeasterly trend, which would correspond to one of the shears."[4] If, however, these mountains are considered to have risen on shears oriented 45° to the direction of pressure in both sections, there must have been considerable horizontal displacement along the fault planes. According to this interpretation, Steens

[1] *Ibid.*, p. 436.

[2] *Op. cit.*, pp. 433–37.

[3] Smith's Fig. 7, labeled "Result of the Compression of an Oak Beam Simulating Formation of a *Graben* (after Emmons)," is an entirely different drawing from the one in Emmons' textbook. W. B. Lang, who conducted the experiments on timbers cited by Emmons (*The Principles of Economic Geology*, [New York, 1919], pp. 179–81), states in a personal communication that the experimental piece used was a cylindrical column instead of a beam and that the zones of shear are at an angle of approximately 45° to the direction of compression.

[4] *Op. cit.*, p. 434.

Mountain moved northward in relation to the Alvord graben while the Bluejoint Rim moved southward relative to the adjacent Warner graben.

This horizontal movement entails numerous difficulties. A long fault splinter such as the Wildhorse Spur, which marks the position where one fault dies out and another continues the escarpment, somewhat offset from the first, would be sheared off by this horizontal movement; yet such features are common in southern Oregon. Horizontal movement of the Bluejoint Rim scarp appears to be impossible, for the scarp shows a pronounced series of zigzags and other irregularities which would lock the fault plane against lateral movement. Another obvious difficulty is found in explaining the horizontal movement for those faults which have uniform arclike curves such as Winter Rim and the eastern scarp of Catlow Valley. If the strike of the plane of failure is normal to the direction of thrust, there would be no lateral movement. If, however, the strike were inclined, horizontal movement would occur which would necessitate subsidiary compressional effects in a salient of the thrust block and tensional effects in a re-entrant. No indication of these effects was observed in the blocks bounded by curving and zigzag faults.

Another feature which Smith offers in support of his theory is "the fact that the floors of the several grabens of the region are about the same elevation and do not fall below the general level of the country as a whole."[1] The fact that the graben floors are the side of deposition of recent stream and lacustrine deposits shows, however, that they definitely are at a lower elevation. Near Cedarville, California, which lies in a continuation of the Warner graben known as Surprise Valley, a well penetrated 836 feet of these surficial deposits without striking bed rock.[2] The uniformity of elevation to which Smith refers is apparently the approximately equal elevation of the tops of these deposits. Their uniformity of elevation has no bearing on the origin of the structure.

Owing to lack of exposures through burial beneath these deposits, the underlying structure of the graben floors, in the majority of instances, is purely conjectural. Such evidence as is available, how-

[1] *Ibid.*, p. 436.

[2] Well of Jacob Richsteiner.

ever, indicates that the surfaces of the "down-dropped" blocks are far from uniform in elevation, either in adjacent grabens or within a single graben. At the northern end of Alvord graben, near its eastern border, the summits of a series of westward-tilting fault blocks emerge from beneath the alluvial mantle. If these blocks are projected with the same inclination until they strike the opposite bounding wall of the graben, their western ends would be buried hundreds of feet beneath the surficial covering. In Warner graben the tops of similarly titled fault blocks emerge from the recent lake deposits at a number of localities.

Although Smith is very emphatic in stating that the graben floors cannot sink while under a state of compression, other writers who favor the compressional hypothesis are equally sure that sinkage would be the necessary result.[1]

Still another feature cited by Smith in support of his hypothesis is the "lack of evidence of a void below the arched rocks into which the central portion could drop."[2] The lack of evidence of a previous arch renders this statement irrelevant, but if it is absolutely essential to have a "void," the proximity of the volcanic vents to the graben floor suggests an excuse for one. It seems to the writers unsafe, however, to conclude that the depression of a portion of the earth's crust cannot take place without the presence of a void below the depressed area. It is also entirely unnecessary to assume that sinking (other than relative to the bounding scarps) has occurred in the formation of a tensional graben. The structure may have been produced entirely by differential uplift.

Three other arguments are advanced by Smith[3] in his summary of the evidence against explaining Steens Mountain by tensional faulting. One of these, to the effect that there are "no visible normal fault planes of any magnitude," does not merit further discussion in view of the field evidence already presented. A second contention, based on the folding and warping of the Steens block, was discussed in an earlier part of this paper. The third, stating that "from the

[1] E. J. Wayland, *op. cit.*, p. 357; Bailey Willis, "Dead Sea Problem: Rift Valley or Ramp Valley?" *Bull. Geol. Soc. Amer.*, Vol. XXXIX (1928), p. 536, also p. 512, Fig. 6.

[2] *Op. cit.*, p. 436. [3] *Ibid.*, p. 436–437.

simple mechanics of the problem, any material down-dropping of the central portion of an arch is apparently highly improbable," is irrelevant since there is no evidence of arching by compression prior to, or concomitant with, the faulting.

The writers propose nothing new regarding the mechanics of graben-forming. They find the old explanation of regional tension combined with vertical movement entirely adequate to account for the structural features of southern Oregon. The newer hypothesis of compressional faulting does not accord with the facts imposed by a study of the field relations.

The writers gratefully acknowledge the helpful criticism of Professor C. R. Longwell.

ALTERED TUFFS IN THE ORDOVICIAN OF MINNESOTA

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ABSTRACT

Near the base of the Decorah shale in Minnesota is a thin clay layer that represents an altered pyroclastic deposit, for it consists of montmorillonite retaining a pumiceous texture and contains sanidine, quartz, biotite, apatite, and zircon. It differs materially from the associated sediments, but resembles the Ordovician bentonites of Kentucky and Tennessee with which it has been correlated. The clay of the St. Peter–Platteville transition zone appears to be a normal Ordovician sediment and gives no suggestion of volcanic origin.

INTRODUCTION AND ACKNOWLEDGMENTS

The investigations of Hewett,[1] Wherry,[2] Spence,[3] Ross and Shannon,[4] and others show that certain clays which are composed of micaceous minerals have the textures and minerals of volcanic tuffs and were formed from them by a process of alteration that did not destroy the texture. Ross[5] has summarized the features that are useful in determining altered volcanic materials or bentonites, and he has listed them in the order of their apparent reliability as follows:

Presence of glass relict structure
Presence of minerals and crystal forms characteristic of volcanic rocks (euhedral, zoned, etc.)
Absence of minerals that do not have a volcanic origin (microcline, garnet, muscovite, calcic and soda plagioclase) in the same specimen
Waxy luster
Reaction to water
Optical properties
Chemical properties

[1] D. F. Hewett, "The Origin of Bentonite," *Jour. Wash. Acad. Sci.*, Vol. VII (1917), pp. 196–98.

[2] E. T. Wherry, "Clay Derived from Volcanic Dust in the Pierre of South Dakota," *ibid.*, pp. 576–83.

[3] H. S. Spence, "Bentonite," *Can. Dept. Mines, Mines Brach. No. 626* (1924).

[4] C. S. Ross and E. V. Shannon, "The Minerals of Bentonite and Related Clays and Their Physical Properties," *Jour. Amer. Ceramic Soc.*, Vol. IX (1926), pp. 77–97.

[5] C. S. Ross, "Altered Paleozoic Volcanic Materials and Their Recognition," *Bull. Amer. Assoc. Pet. Geologists*, Vol. XII (1927), p. 149.

The present paper reports for the first time the textural, mineralogical, and chemical evidence for Ordovician volcanic activity in Minnesota. During this investigation thirty-seven thin sections of the altered tuff from the Twin City Brick Plant, from along the Mississippi River below the Franklin Avenue Bridge and at the High Dam, and from Faribault, Minnesota, were compared with those of the associated sediments as well as materials from other localities. The conclusions herein stated are based largely upon this study.

The writer is indebted to Professor Clinton R. Stauffer for his assistance during a visit to the Twin City localities and for his generosity in contributing specimens from his collections for study. The writer also acknowledges the suggestions and criticism of Professors Frank F. Grout and R. J. Leonard.

THE FIELD SECTION

The stratigraphic position of the beds to be discussed is shown in a generalized section given by Stauffer[1] from exposures at the Ford Automobile Factory in St. Paul:

	Thickness Feet	Inches
DECORAH:		
9. Shale, argillaceous, soft, blue, alternating with occasional layers and lenses of blue limestone	30±	
8. Limestone, gray to bluish	2	0
7. Shale, soft, gray to bluish white	0	3
6. Limestone, dolomitic, hard, coarse, rough, brown in color	1	6
PLATTEVILLE LIMESTONE:		
5. Limestone, dolomitic, gray to bluish	8	0
4. Limestone, dolomitic, shaly, blue in color	6	0
3. Limestone, compact, hard, blue in color, and with irregular shaly partings	12	0
2. Shale,* bluish, somewhat calcareous and often sandy	3	0
ST. PETER SANDSTONE:		
1. Sandstone, white, poorly cemented	70±	

* In Iowa, the name "Glenwood" has been given to Bed No. 2, by Calvin, *Iowa Geol. Survey*, Vol. XVI (1906), pp. 60, 61, 74.

THE BED OF ALTERED TUFF

The general appearance of the soft gray shale (Bed No. 7 in Stauffer's section) interbedded with the limestone near the base of

[1] Clinton R. Stauffer, "Mineralization of the Platteville-Decorah Contact Zone in the Twin City Region," *Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925), p. 616.

the Decorah is sufficiently different from that of the upper beds that it attracted attention and was mentioned by Grout[1] and by Stauffer.[2] Sardeson[3] has designated it bentonite and the correlative of a bed described by Nelson[4] in Tennessee, Kentucky, and Alabama. Locally, this shale, 3 inches or so in thickness, is called the "putty layer." In the hand specimen, the color is generally light gray to bluish gray, rarely buff, and some specimens have a waxy translucence that Ross[5] states to be characteristic of bentonites, and which the writer has observed in connection with altered Tertiary tuffs of California. At the outcrop, the shale is saturated with water which trickles from the overlying rocks even long after a rain, and under this condition the shale becomes a plastic sticky clay. Vegetation quickly becomes rooted in the moist seam upon its exposure, and both these factors make it difficult to secure a sample in an undisturbed condition.

In thin section the shale consists largely of a mineral with a micaceous habit that has a birefringence of about 0.03, and large areas of which extinguish at the same time under crossed nicols. The index of refraction of β determined by the immersion method varied in the samples examined from 1.523 ± 0.005 to 1.535 ± 0.005. The optical character is negative, and $2V$ equals 20°–30°. These properties are close to those of[6] montmorillonite, in which it is known that an excess of alkalies or a loss of water will cause a variation in the indices of refraction. A few of the larger areas composed of this mineral have a texture similar to pumice fragments with minute

[1] F. F. Grout, "Clays and Shales of Minnesota," *U. S. Geol. Survey Bull. 678* (1919), p. 150.

[2] *Loc. cit.*

[3] Frederick W. Sardeson, "Volcanic Ash in Ordovicic Rocks of Minnesota," *Pan-American Geologist*, Vol. XLII (1924), pp. 45–52; "Beloit Formation and Bentonite," *ibid.*, Vol. XLV (1926), pp. 383–92; Vol. XLVI (1926), pp. 11–24; "Ordovicic Bentonite in the Northwest," *ibid.*, Vol. XLVIII (1927), pp. 347–54; "Bentonite Seams in Stratigraphic Correlation," *ibid.*, Vol. L (1928), pp. 107–16.

[4] Wilbur A. Nelson, "Volcanic Ash Bed in the Ordovician of Tennessee, Kentucky, and Alabama." *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), pp. 605–16.

[5] Clarence S. Ross, "Altered Paleozoic Volcanic Materials and Their Recognition," *Bull. Amer. Assoc. Pet. Geol.*, Vol. XII (1927), p. 147.

[6] Clarence S. Ross and E. V. Shannon, "The Minerals of Bentonite and Related Clays and Their Physical Properties," *Jour. Amer. Ceramic Soc.*, Vol. IX (1926), p. 95.

elongate vesicular cavities (see Figs. 1, 2), and this is suggestive that the montmorillonite has formed from volcanic glass with the reten-

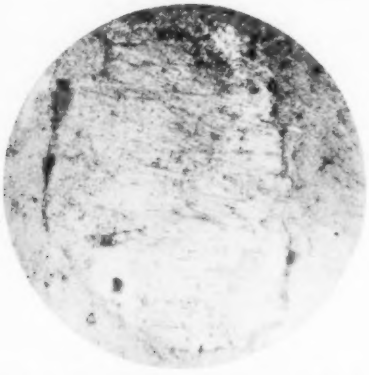

FIG. 1.—Fragment of pumice altered to montmorillonite. "Putty layer" in Decorah shale. Twin City Brick Co., St. Paul. ×30.

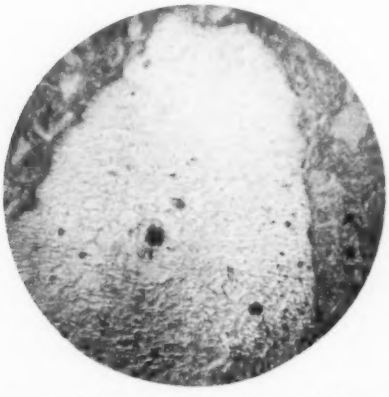

FIG. 2.—Showing parallelism of elongate glassy vesicular cavities in a rhyolite vitric tuff. Suggestions of this texture have been retained during the alteration of the fragment shown in Fig. 1. Jackson Quadrangle, California. ×30.

tion of its structure. The next abundant mineral is feldspar occurring in angular, broken, or embayed crystals. In two sections, a small amount of pale-brown biotite was observed. For the purpose

of study, the sandy grains were concentrated by repeated washing and decanting of large samples and finally were separated into two groups with bromoform. In most samples, the heavy minerals consist of zircon, apatite, magnetite, and pyrite. The zircon and apatite are euhedral, with pyramidal terminations often perfectly developed. The pyrite is euhedral, and octohedrons, cubes, pyritohedrons, and twins have been observed. It is an authigenic mineral, and its origin has been discussed by Stauffer.[1] In one sample taken along the Mississippi River some distance below the Franklin Avenue Bridge,

TABLE I

	1	2	3	4
SiO_2	51.45	51.27	51.75	57.47
Al_2O_3, etc.	26.00	25.09	26.39	23.29
CaO	1.09	1.25	1.89	0.45
MgO	4.04	4.44	3.00	1.86
H_2O (100–110)	5.00	4.82	3.80	2.54
H_2O (135–50)	0.70	0.76	0.50	0.42
H_2O (185–95)	0.20	0.14	0.18	.....
H_2O red heat	5.63	6.32	6.08	3.14
Undetermined	5.89	5.91	6.41	10.83
	100.00	100.00	100.00	100.00

1. Material from High Dam, Minneapolis.
2. Material from Twin City Brick Plant, St. Paul.
3. Material from Twin City Brick Plant, St. Paul.
4. Material from Faribault, Minn. (R. J. Leonard analyst).

Minneapolis, rounded grains of garnet, brown tourmaline, green hornblende, and epidote were found along with euhedral zircon and apatite. The light minerals usually consist of quartz and feldspar. The optical properties of the feldspar suggest soda sanidine, for the optic angle is very small and an indistinct grating is present in some grains under crossed nicols. Some of the quartz grains are angular; others are rounded to a degree equaled only by those of the St. Peter sandstone.

In 1924 R. J. Leonard commenced a chemical investigation of this clay at the University of Minnesota, and through his courtesy the accumulated data appear in Table I. Owing to more pressing duties at the time, a microscopic study was not undertaken. The

[1] *Loc. cit.*

results did not conclusively prove its origin, but it was considered that the physical properties, especially lacking the tendency to swell when immersed in water, were opposed to its being classed as bentonite.

Experiments[1] made on bentonite show that when it is boiled with a five times normal solution of sulphuric acid for five hours, the colloidal properties are destroyed; that about 85 per cent of the aluminum oxide goes into solution as aluminum sulphate, along with the alkalies present, but all the silica except a trace remains undissolved. According to the foregoing statement, Leonard treated the samples

TABLE II

	1	2	3	4
Residue after H_2SO_4 treatment	54.55	55.41	56.96	75.10
SiO_2	85.57	87.24	83.78	72.21
Al_2O_3, etc.	4.30	3.27	6.21	13.72
CaO	0.03	0.05	Tr	0.03
MgO	0.86	0.55	0.66	0.50
Percentage of Al_2O_3 going into solution	91.07	92.91	86.81	56.66
Percentage of SiO_2 going into solution	9.54	6.00	8.06	5.88

of the Decorah "putty layer," with the results shown in Table II. For convenience, the analyses of the Decorah shale overlying the "putty seam" at St. Paul, and the bentonites at Singleton, Tennessee, and High Bridge, Kentucky, are shown in Table III.

COMPARISON WITH THE ASSOCIATED BEDS

A comparison of the chemical analyses of the "putty layer" with those of the overlying Decorah shale and the bentonites of Kentucky and Tennessee shows similarities and differences that are not always consistent throughout all the samples. The petrographic evidence is somewhat more decisive. A typical sample of Decorah shale furnished by Dr. Stauffer from about 20 feet above the base of that formation at the Ford plant was studied in the same manner as the "putty layer." The clay mineral composing it has an index of refraction of about $1.563 \pm .005$, and tuffaceous structures were not observed in it. Ordinarily it is somewhat calcareous, and in thin

[1] Wilbur A. Nelson, *op. cit.*, p. 616.

section rhombs of calcite are distributed throughout the clayey material. Attempts to concentrate the sandy grains by treating samples of equal size, and by the same procedure as the "putty layer," disclosed the absence of soda sanidine and euhedral zircon. The "putty layer" thus appears to differ from the normal Decorah shale in its dominant clay mineral, in its texture, and in its associated minerals.

TABLE III

	5	6	7	8	9
SiO_2	56.35	54.66	50.81	54.80	54.56
Al_2O_3	18.63	24.04	20.25	22.93	19.97
Fe_2O_3	6.19	6.53	5.18	1.91	0.69
FeO				0.45	1.28
CaO	0.96	0.45	4.05	1.20	1.08
MgO	2.97	1.08	2.13	3.10	5.08
P_2O_5	*nd*	*nd*	*nd*	0.13	0.15
TiO_2	0.65	0.66	0.50	*nd*	*nd*
F	*nd*	*nd*	*nd*	0.11	0.13
K_2O	7.37	5.37	5.69	2.04	4.06
Na_2O	0.25	0.47	0.28	4.12	1.66
H_2O (100–110° C.)	2.41	2.35	2.16	4.58	6.62
H_2 (150–60° C.)				0.68	0.48
H_2O (200–210° C.)				0.52	0.32
Red heat	4.81	5.15	8.92	3.83	4.52
	100.59	100.76	99.97	100.40	100.60

5. Lower Decorah shale, west St. Paul (F. F. Grout).

6. Lower Decorah shale, west St. Paul (F. F. Grout).

7. Upper Decorah shale, west St. Paul (F. F. Grout).

5, 6, 7. Listed by F. F. Grout in *Clays and Shales of Minnesota, U.S. Geol. Survey Bull. 678* (1919), p. 152.

8. Bentonite from road cut on the Dixie Highway at Singleton, Bedford Co., Tenn. (analysis by D. F. Farrar).

9. Bentonite from High Bridge, Ky. (analysis by D. F. Farrar).

8 and 9 listed by Nelson, *op. cit.* (1922), p. 614.

Specimens of the St. Peter-Platteville transition zone from the outcrops along the Mississippi River near the University of Minnesota were also studied. The stratigraphic position of these would correspond to Bed No. 2 in Stauffer's section and to the beds in Iowa called "Glenwood" by Calvin. The bluish clay in which the sand grains are imbedded resembles the Decorah shale in refractive index and in texture. Washed samples yielded well-rounded quartz, garnets, zircon, tourmaline, and euhedral authigenic pyrite, but no soda

feldspar. There is no evidence that it is an altered tuff, and, contrary to the suggestion of Sardeson,[1] it is similar in these respects to the usual clay deposited in that region during the Ordovician. The thin sections reveal no suggestion that what are now clay grains were deposited as larger fragments. It is true that later alteration might destroy most of these, but since the "putty layer" contains some large fragments, and as none was observed in the transitional zone, it is reasonable to assume that none was deposited. There remains the possibility that the St. Peter sands were mixed with fine clay materials to produce the transitional zone. It is a common occurrence to find that sandstones are more shaly as the contact with the overlying limestone is approached. For example, in Missouri are recorded[2] shales between the Lamotte sandstone and the Bonneterre dolomite. Numerous others could be cited. The presence of sand grains imbedded in the clay is not unique, for in the Ione Delta[3] formation of California are clays, lacking well-defined bedding and containing disseminated angular quartz grains, that are quite similar texturally to the mixture of the transition zone.

COMPARISON WITH ORDOVICIAN BENTONITES

While the chemical composition of the "putty layer" resembles the overlying Decorah shale almost equally as well as the bentonites of Kentucky and Tennessee, in their reactions to the H_2SO_4 treatment, samples 1, 2, and 3 behave similarly to the bentonites treated by Nelson. It may be pertinent, here, to recall the minerals reported by Larsen[4] in the bentonites examined for Nelson. The chief clay mineral was determined as leverrierite, but later study by Ross[5] and Shannon has shown it to be montmorillonite. Larsen, also, observed soda orthoclase in broken or embayed crystals, and in addition quartz, apatite, zircon, and a little colorless mica. With the exception of the colorless mica, these are the minerals of the putty layer, and in Minnesota are limited to it, for the samples of ordinary Decorah shale and the Glenwood beds that were examined lack the

[1] *Op. cit.* (1926), p. 386.

[2] E. R. Buckley, "Geology of Disseminated Lead Deposits of St. Francois and Washington Counties," *Mo. Bur. of Mines and Geol.*, Vol. IX (1908), p. 28.

[3] Victor T. Allen, "The Ione Formation of California," to appear in *Univ. Calif. Pub. Bull. Dept. Geol.*

[4] Quoted by W. A. Nelson, *loc. cit.* [5] *Loc. cit.*

most essential ones. The soda feldspar of the "putty layer" is believed to be sanidine because of its very small optic angle, and this is a significant point, as sanidine is limited in occurrence to volcanic rocks. The texture of the "putty layer," its minerals and the forms in which they occur, its limitation to a thin layer differing from the beds above and below, are best explained by considering it an altered volcanic tuff.

The presence of brachiopod casts and the more numerous remains of bryozoa imbedded in the "putty layer" testify that it accumulated in the sea. Did the volcanic materials fall directly from the air into the water, or were they washed there from some previously accumulated volcanic deposit? The question is of great importance in correlation, yet the evidence suggests only a partial answer. In the "putty layer" are rounded grains of quartz and in one sample round garnets, tourmalines, and epidotes, and these are foreign to a true volcanic deposit. In the same samples are angular sanidine feldspar, euhedral zircon, and apatite, and these could not have been subjected to the same conditions of transportation that rounded the quartz and the non-volcanic minerals. The assemblage is easily explained by considering that the material came from two sources. All the rounded minerals, with identical spherical forms, have been observed by the writer in the St. Peter sandstone, and it is possible they came from that formation. But, whether they were contributed to the "putty layer" by ocean currents as the volcanic materials slowly settled to the bottom, or whether they were gathered by the wind from a land area and transported via the air along with the *ejecta* from a distant volcano, cannot be decided satisfactorily. That the "putty layer," however, is not a re-worked tuff is more firmly assured, if it came from the same vent as the thicker Ordovician volcanic deposits of Kentucky and Tennessee, to which it is similar, for if transported by water a goodly part of that distance, there should be left some visible effects on the volcanic minerals, and these are absent.

THE QUESTION OF NOMENCLATURE

Whether this altered tuff should be called "bentonite" is a question which may occur to some. Giles[1] has recently discussed the

[1] Albert W. Giles, "The Origin and Occurrence in Rockbridge County, Virginia, of So-called 'Bentonite,'" *Jour. of Geol.*, Vol. XXXV (1927), pp. 535–37.

definition of bentonite, and reviewed some of the diverse usages of the term. If economic adaptability is to be taken as a criterion, the name is not applicable to the Minnesota deposit, as the separate commercial utilization of a clay bed 3 inches or so in thickness is doubtful, even if the physical properties were satisfactory. As the term has been used by Ross[1] and Shannon, the material is bentonite, but it lacks, as Leonard found, some of the properties that others consider are fundamental requisites. To the geologist the genesis of a clay is more important than its physical properties, and in indicating the origin and nature of this clay, the writer is willing to leave its classification in abeyance until there is a more general agreement on the nomenclature of clay.

[1] *Loc. cit.*

DRAINAGE ALIGNMENT IN THE WESTERN GREAT PLAINS[1]

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ABSTRACT

In scattered areas over a great extent of the western Great Plains there is a very marked drainage alignment. It is shown that this cannot have been produced by the normal development of the drainage or by regional tilting. In certain restricted areas an alignment in a general northwesterly direction has been produced by structural deformation, but over the greater part of the area structural control has not been effective. In parts of southwestern Nebraska a very pronounced alignment has been produced by the deposition of sand by northwest winds, and it is probable that the alignment elsewhere has been produced in the same manner, and the sand deposits removed by erosion.

INTRODUCTION

One of the most remarkable features of the northwestern Great Plains is the well-defined northwest-southeast alignment of the valleys and ridges. The prevailing direction of the valleys and ridges is nearly identical over such great areas that it is evident that the causes or forces which produced the parallelism must have operated on a grand scale. Hence the question of the mode of origin of the alignment constitutes one of the important regional problems of the province in which they occur.

THE NATURE AND OCCURRENCE OF THE ALIGNMENT

The alignment is developed in parts of western South Dakota, western Nebraska, western North Dakota, eastern Montana, and eastern Wyoming. The areas in which it is known to occur, and its prevailing direction, are shown in Figure 1. The material for this map was obtained from the U. S. G. S. topographic maps, county maps, state survey reports, the U. S. G. S. state maps on the scale of 1/500,000, and, in a few places, from the investigations of the writer. If topographic maps were available for all of the area covered by Figure 1, it is probable that the alignment would be found to occur in

[1] Data relating to South Dakota form portion of dissertation submitted as part requirement for the degree of Doctor of Philosophy at Yale University, and are published by permission of the State Geological Survey of South Dakota. The writer is indebted to Professor C. R. Longwell for a criticism of the manuscript, and to the Etnyre Syndicate for the loan of an automobile for use in the investigation in Nebraska.

additional territory, for there are extensive areas in western Nebraska and eastern Wyoming in which it may exist, but in which it cannot be mapped for lack of data.

In spite of this lack of information in certain regions, however, the alignment is known over a general area of about 125,000 square miles, though inside the confines of this tract there are wide stretches in which it cannot be detected. As shown by Figure 1, this general area in which it is known extends from Lyman County, South Dakota, to the Mussellshell River in central Montana, an east-west distance of about 400 miles, and from the northeast corner of Colorado to the junction of Milk River with the Missouri River in northeastern Montana, a north-south distance of about 450 miles.

The alignment is shown much more clearly by the small draws, ridges, and buttes than by the larger creeks and divides, while the larger rivers are not affected at all. It is best illustrated by the topographic maps of the Pierre Quadrangle, South Dakota, and the Chappel Quadrangle, Nebraska. The direction of the alignment averages about north 45 degrees west, though it apparently varies from north 40 degrees west to north 50 degrees west. In southern Nebraska, as indicated by Figure 1, there is a prevailing north-south trend of the ridges and streams, and in one place there seems to be a northeast-southwesterly trend. The formations in which the alignment is developed are in part Cretaceous and in part Tertiary, ranging from the Pierre to the Ogallala. Further data on the geology of the area in which it occurs will be given by the writer in a bulletin of the State Geological Survey of South Dakota.[1]

The map, Figure 1, was constructed to show only the alignments which could not be explained as being due to the outcrops of unequally resistant formations, or as being due to the normal development of the topography. Hence, the marked northwest trend of the ridges and valleys in the Black Hills is not shown, for it is parallel to the strike of the strata, and obviously produced by the erosion of unequally resistant formations. Where the minor stream courses are at right angles to those of the major rivers there is in many places a marked alignment. As, however, there is normally a tendency for

[1] W. L. Russell, "Stratigraphy and Structure in the Cretaceous of Western South Dakota," *South Dakota State Geological Survey, Bull. 14* (in press).

the surface to slope from the major divides toward the larger rivers, such an alignment might be supposed to develop under normal conditions. Hence, where the trends are of this nature they are not shown in Figure 1. When, on the other hand, the prevailing trend of the minor creeks cuts diagonally across the larger rivers, then there is a tendency for the streams on one side of the main valley to hook back, so that they join the main river from the downstream side. As such a drainage pattern would not normally develop, its existence over such a great area raises problems concerning its origin.

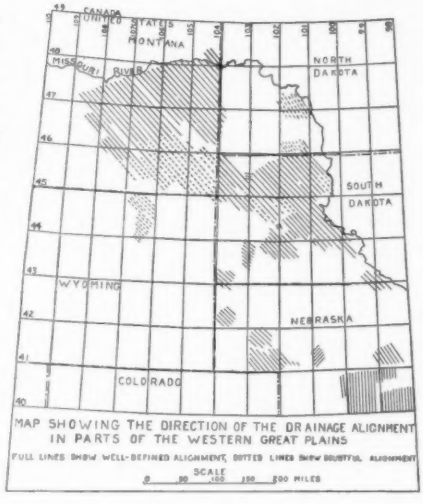

FIG. 1

THE ORIGIN OF THE ALIGNMENT

Although it appears that two processes—structural deformation and wind action—have produced the alignment, it may be well to mention all the possible causes and the evidence relating to them. Four different hypotheses of origin may be cited: the influence of the prevailing slope of the surface, the erosion of weak and resistant strata along the regional strike, structural deformation, and wind action. Although there is no doubt that a marked drainage alignment may be produced simply by virtue of a uniform slope of the surface, it does not appear that this explanation fits the facts in the present case. In the first place, the direction of the courses of the major streams is not northwest-southeast, but west-east. If there had been a general slope sufficient to produce such a profound alteration in the drainage, one would think that the main streams would be influenced. It is also difficult to explain how the regional slope

could have been from the northwest to the southeast, for at present it is from west to east, or west-southwest to east-northeast, and there is no reason to suppose that there was at any time since the late Tertiary a pronounced uniform tilting in a southeasterly direction. As the alignment is known to occur in the Ogallala formation, which is of Miocene or Pliocene age, and as the Black Hills have been in existence since pre-Tertiary time, one would expect that the general slope would be partly away from this structure and away from the other uplifts farther west. Yet, as will be seen from Figure 1, no influence of these highlands appears in the direction of the alignment.

The second explanation may be also dismissed briefly. It is certain that over much of the area the alignment is not parallel to the general strike of the formations. In western South Dakota there is not the slightest relation between the direction of the alignment and the direction of the strike. The latter changes completely while the former continues in the same direction. Moreover, the Pierre shale and some of the other formations in which the alignment is extensively developed are so uniform in their character that the difference in the manner of erosion of their different members could scarcely have exerted any important effect on the topography. Furthermore, in much of the area the regional dips are too low to produce such marked ridges and valleys by differential erosion. In great areas in western South Dakota the regional dip is only about ten feet per mile.

In southwestern Nebraska, where a marked alignment is developed between the North and South Platte rivers, there is no sign of any relation between the direction of the alignment and the strike of the strata. The Ogallala formation, which is the bed rock of this region, dips gently to the east-southeast or southeast at a rate of roughly 10 to 20 feet per mile, while the ridges and valleys trend north 45 degrees west with surprising regularity. The regional dip is, moreover, too slight to have produced such a marked series of closely spaced ridges and valleys by the differential erosion of unequally resistant strata. The beds of the Ogallala formation differ considerably in their hardness, but this appears to have had no appreciable effect on the topography. Toward the east, in the vicinity of Ogallala, the ridges rest on a thick bed of unconsolidated sand and gravel

in the Ogallala formation. Further west, in the vicinity of Oshkosh, ridges of the same type are developed on the harder sandstones and limestones which lie below the gravel bed.

Although there is no relation between the alignment and the regional dip, an alignment of the ridges and valleys in a general northwest direction has in places been produced by sharp local dips or by faulting. In certain parts of western South Dakota there are folds which extend in a northwest direction and which have apparently produced northwest-southeast ridges and valleys. In the northwestern great plains there is a general tendency for anticlines to occur in ridges and for synclines to lie in valleys. This relationship is probably produced by the effects of differential erosion of beds of unequal hardness, and possibly also by the preservation of the original uplifts and depressions caused by the folding. In the plains of western South Dakota, where the folds were probably covered nonconformably by flat-lying Arikaree beds, and then exposed by the removal of the Arikaree, the correspondence between the topography and the structure is presumably due to the rapid erosion of the White River strata.

In eastern Harding County in the vicinity of the northern Slim Buttes a system of fault blocks has produced ridges and valleys with a marked west-northwest trend. Here also the valleys and ridges have been produced by the rapid erosion of the White River formation compared with the underlying strata. Hence it is only developed where the White River has been largely eroded away. In a small area in eastern Pennington and western Haakon counties a northwest trend has been produced by another series of fault blocks which are small but highly tilted.[1] In this case the ridges and valleys are produced by the differential erosion of hard calcareous Fox Hills sandstones and the soft shales associated with them. These areas are indicated in Figure 1.

It appears, however, that it is only locally that the northwest alignment has been produced by the differential erosion of hard and soft strata. It is scarcely likely that ridges and valleys could be produced in this manner unless the uplifts and depressions due to the deformation were of a size that could be readily recognized in struc-

[1] W. L. Russell, "Structures in Eastern Pennington and Western Haakon Counties," *S. D. Geol. and Nat. Hist. Survey, Circular No. 28.*

tural work. Yet in some of the areas in western South Dakota where the alignment is well defined, as for example in southern Haakon County, there is no sign of any northwest-southeast folding or faulting of such magnitude, and in other localities where there is folding and faulting there is no indication that such structures have any prevailing trend.

It is possible that deformation has produced a series of parallel joints or fissures which have served as channels for solutions which deposited cement in the sandstones adjoining the fissures. If such highly cemented belts were developed, they would tend to form parallel ridges when eroded. However, there is no positive indication that this has ever taken place, and moreover a study of the Tertiary deposits of the region suggests that their cement was formed chiefly during deposition.

It appears that eolian action is capable of producing alignment of the kind under discussion, for the parallel ridges and valleys between the North and South Platte rivers in Nebraska have clearly been formed in this manner. Fortunately these ridges abut on the north on the zone of badlands on the south side of the North Platte River, and for this reason it is possible to obtain accurate data on the character and structure of the formations which underlie the parallel ridges and valleys. Aside from a very gentle regional dip, these strata are practically undisturbed, and there is no sign of any faulting, sharp dips, or irregularities of cementation which could have produced any important topographic effects.

The ridges themselves are composed of very fine yellowish-white or grayish-white sand of a strikingly uniform appearance. No exposures of the Ogallala formation could be found in the ridges, and pebbles and fragments derived from this formation were likewise absent, though they are common on the adjoining plains and valleys. The fine sand is not a superficial deposit, for some of the gullies which cut the ridges have vertical walls of this material 50 feet high, and the depth of these gullies is in some cases 75 feet or more. The sand generally exhibits a banding or lamination, which is mostly horizontal. Large-scale cross-bedding, which is said to be characteristic of eolian deposits, is absent, but cross-bedding in zones six inches to one foot high is fairly common. The oblique lamination

generally dips to the southeast, suggesting a source to the northwest. The sand has very much the same appearance as loess, though it appears to be slightly coarser and cleaner. It is also similar to loess in its manner of eroding and standing in vertical cliffs. The grains of the sand are chiefly from .02 to .15 mm. in diameter. Most of them are subrounded to subangular, but some are quite round. When thrown into the air, most of the sand floats away on a gentle breeze.

Apparently the sand of which the ridges are composed was brought in by the southwest winds and spread over the surface in sheets. Sand drifting over the surface may have been concentrated at certain points by valleys or other topographic irregularities. Parallel ridges would then tend to be built up extending down the wind from these points of concentration. Valleys would develop between the ridges, and this drainage pattern, once formed, might be preserved during protracted erosion and finally superimposed upon older formations. Additional evidence of the former occurrence of prevailing northwest winds in this general region is found in western Kansas, where the loess has been removed from the northwest slopes of the hills and deposited on the southeast sides.

The parallel ridges of southwestern Nebraska are apparently not in the process of formation at the present time. The 22-mile ridge northwest of Big Spring is crossed by a stream, and many small valleys are developed in the ridges. Moreover, the stream valleys which have been cut below the plain parallel to the ridges indicate that considerable erosion has taken place since the alignment was developed.

In parts of western South Dakota where the alignment is well developed there are no extensive eolian deposits, and the formation at the surface is the Pierre shale, which contains no sand. However, it should be remembered that these regions were once covered by Tertiary deposits which consisted largely of loose sand. In fact, these sandy Tertiary formations must have once covered all the area in which the alignment was developed, for they are now found in small remnants on isolated buttes and mesas throughout this territory. It is possible that the alignment was first produced by eolian action in the manner described, and then superimposed on the shales by continued erosion.

SANDBLAST ACTION IN RELATION TO THE GLACIERS OF THE SIERRA NEVADA

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ABSTRACT

That effective wind abrasion depends upon a combination of favoring conditions seems to be illustrated at the mouths of certain canyons in the Sierra Nevada. Winds sweeping along the glacial troughs used the glaciers as floors along which they drifted the finer rock débris against the opposing hills that were not then protected by vegetation. Conspicuous effects are still preserved, although the conditions have ceased to exist.

The action of the natural sandblast carves distinctive features such as pits, grooves, and facets upon various rock surfaces. The effects are of comparatively rare occurrence, even in deserts, because all of the requisite conditions are seldom present. The writer was therefore surprised recently to find surfaces conspicuously chiseled by sand along the eastern base of the Sierra Nevada in California, in situations where wind abrasion is now inhibited and probably ceased long ago.

The wind-carved rock outcrops and boulders were found in several places along the eastern slope of the range both north and south of Mono Lake, but all in similar topographic situations. Near Bridgeport some hills of andesite (Hunewill Hills) stand 800 feet above the plain and athwart the mouth of a deep glacial canyon. Moraines of the old glacier rise within 150–200 feet of the top of these hills. On the southwest slope, facing the canyon, all the rock surfaces are strongly grooved and drilled by the sandblast. On the northeast slope of the hills no such markings were found, but on the contrary the rocks are merely cracked and exfoliated in the ordinary manner. Surfaces that squarely confronted the wind are covered with pits or wells 5–10 millimeters wide and 10–25 millimeters deep, but where the wind was nearly tangent to the surface, long grooves 5–15 millimeters wide were carved out (see Fig. 1).

Regardless of their position on the southwest slope of the hill, the grooves all point directly toward the canyon—usually a little

south of its axis. It is therefore clear that the causative winds blew northwestward down the canyon and were slightly diverted toward the right by the curve in the valley at that point.

At present the local conditions are unfavorable for effective wind abrasion upon these hilltops. Although strong winds blow down the canyon rather frequently, they cross two large lakes before reaching

FIG. 1.—Boulders of andesite carved by wind abrasion near the summit of Hunewill Hills. The wind came from the right. A scale of inches is shown at the base of the largest boulder.

the moraine, and therefore have no opportunity to pick up sand on the floor of the valley. The lakes are not margined by wide beaches from which much sand could be obtained, and the moraine slope up which the wind must then sweep is abrupt and well clothed with sage and other shrubs. The rock outcrops themselves on the upper parts of the hills are now considerably sheltered by stiff mahogany bushes 5 or 10 feet high and a generous growth of sage (Artemisia) 1–2 feet high. These bushes effectively protect the ground from the wind, which is thus unable to pick up sand and drive it against the rock outcrops. That sandblast action is not now in progress on the hill

is clearly shown by the dulled and partly exfoliated condition of the rock surfaces that still retain the sandblast grooving. From this evidence the writer infers that the carving was done by sand-laden winds of an earlier epoch, at a time when conditions were decidedly different from those now prevalent in the Bridgeport district.

To understand the observed facts it is profitable to imagine the conditions of the locality during the late Pleistocene epoch. At that

FIG. 2.—A detail of the surface of an andesite boulder showing the characteristic effects of eolian abrasion. The pencil on the left indicates the scale and the depth of the pits.

time Robinson Canyon was occupied by a long glacial tongue that extended itself out from the cirques along the main divide to a length of about 11 miles. The glacier was about 700 feet thick and formed a comparatively smooth roadway about 1 mile wide and less than 200 feet below the summit of the andesite hills. At present none of the small glaciers that still linger near the Sierra Nevada divide descend below timberline. If the same was true during the glacial epoch, the top of the andesite hills may have been considerably above the timberline of that age and hence largely devoid of effective

protection. The lower part of the glacial tongue was probably more or less covered with ablation moraine, and along its immediate margin a prominent lateral moraine was being formed. Strong winds concentrated in the glacial trough would doubtless have had but little difficulty in sweeping the finer particles of this glacial detritus

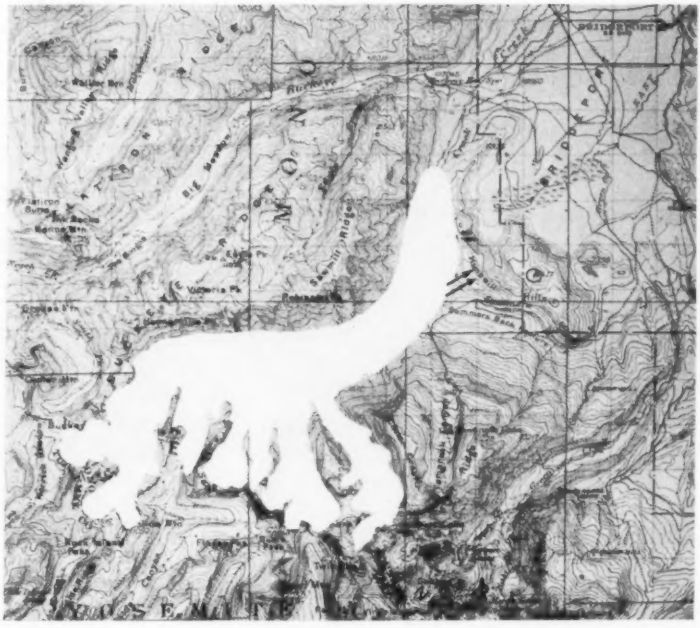

FIG. 3.—Contour map of the Bridgeport district, representing the Twin Lakes glacier as it probably existed during the last glacial epoch. The position and orientation of the grooves made by the sandblast are indicated by the arrows. (Base map by U.S. Geological Survey.)

over the gentle upper slopes of the andesite hills with such velocity as to chisel and groove the solid rocks and leave the distinctive sculptural effects that are now to be observed there. It is interesting to note in this connection that active sandblast action is now in progress on the margin of some of the glaciers in Iceland, as described

recently by Samuelsson and Nielsen in papers that have been reviewed by Antevs.[1]

Sandblast effects like those on the Hunewill Hills, but in general not as severe, have been observed by the writer on the old glacial moraine north of June Lake,[2] and on the rocky hills near the mouth of Rock Creek Canyon northwest of Bishop. No doubt similar effects will be found in other localities along the range wherever hills stood opposed to the icy blasts that swept down along the glaciers of late Pleistocene time.

[1] Ernst Antevs, Abstract, "Wind Deserts in Iceland," *Geog. Rev.*, October, 1928, p. 675.

[2] The grooving of the boulders of granite at this place had been noted and correctly diagnosed by I. C. Russell ("Quaternary History of Mono Valley, California," *U.S. Geol. Surv. Ann. Rep.*, Vol. VIII [1889], p. 388).

A FRESH SKULL OF AN EXTINCT AMERICAN CAMEL

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ABSTRACT

A fresh-appearing skull of a camelid, from a cave in Utah, is described and figured. It is referable to the genus *Camelops*, and indicates the survival of the native "camel" until comparatively recent times.

In a recent number of *Science*[1] a preliminary account was given of a skull referable to the native American camelid genus *Camelops*, brought to the writer by Professor A. L. Matthews, of the University of Utah. The specimen, found in a cave in the region of Fillmore, Utah, was in remarkably fresh condition, no replacement of the bone having taken place, and the remains of organic material still being present. Since the Camelidae had been supposed previously to have been extinct on this continent since the Aftonian interglacial stage, the skull is obviously an important document in the history of the American Pleistocene; it is the object of this paper to place it on record.

The remains consist of the brain case and the greater portion of the palate of a young animal. It is impossible to show by photographs the very fresh appearance of the specimen at the present time. The dorsal surface is dried out superficially, but fresh breaks present a yellow appearance, indicating the oil content to be still rather high. On the ventral surface (Fig. 1) are two masses of brownish material which are obviously the remains of the rectus capitis muscles (most of this has since been removed for study). Other organic matter is present in the suture between basisphenoid and presphenoid. Obviously no great antiquity can be attributed to a specimen in this comparatively fresh condition, even under the most favorable conditions.

[1] *Science*, n. s., Vol. LXVIII (July 6, 1928), pp. 19–20.

Brain case—ventral surface (*Fig. 1*).—The region of the tympanic bulla is obviously of camelid type. The anterior portion of it, however, is thicker than in the living camels, a feature in which it resembles *Camelops* as described by Merriam.[1] The basisphenoid and presphenoid present a prominent V-shaped ridge on the ventral surface as in *Camelops*, while, as noted by Merriam, this region is low and rounded in *Camelus*. The muscular markings on the basioccipital

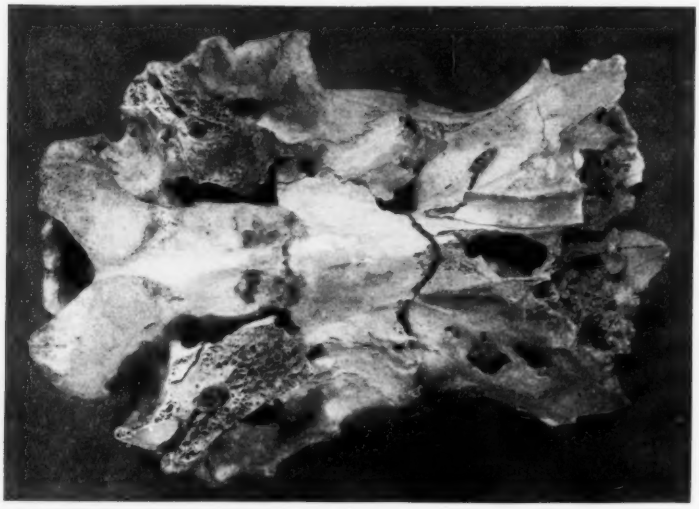

FIG. 1.—Ventral view of braincase, $\times\frac{1}{2}$. Remains of muscle material visible on basioccipital, and other organic material in the basisphenoid-presphenoid suture. Lack of an internal lip on the glenoid, the ridged basisphenoid, the thickened anterior end of the tympanic bulla, and the apposition of mastoid and paroccipital may be noted.

and basisphenoid are not prominent, presumably due to the immaturity of the animal. The internal margin of the glenoid is not clearly set off from the region medial to it, the situation being similar to that found in *Camelops;* in contrast, the living camels have a well-marked raised border, even in young specimens. The mastoid and

[1] University of California Publications, *Bull. Dept. Geol.* 7, No. 14 (1913). Two skulls of *Camelops* from Rancho la Brea are described and figured. One (No. 20040) is identified as *C. hesternus;* a second (No. 20028), differing in some features, especially of the palate, is treated as "*Camelops* near *hesternus*."

paroccipital may be seen to be closely united for much of their length, as described by Merriam in *Camelops;* in the Old World camels these processes diverge externally to a considerable degree.

Brain case—lateral surface (*Fig. 2*).—It will be noted that the glenoid is situated well up the side of the brain case, in contrast with living camels, in which it is low down and nearly opposite the ventral surface of the basisphenoid. This higher position causes a marked

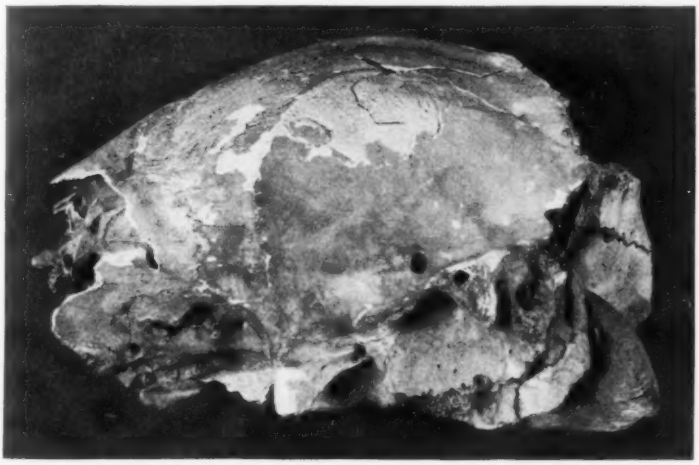

FIG. 2.—Lateral view of braincase, ×½. Showing high position of the glenoid, the accessory foramen visible in the broken end of the glenoid process, and the intimate union of mastoid and paroccipital.

difference in the relations of the glenoid portion of the squamosal to adjacent structures and implies that the posterior portion of the zygoma was considerably raised. The condition here is very similar to that found in the skulls of *Camelops* from La Brea. The postglenoid foramen (not visible in the figure) is small, as in *Camelops;* it is large in *Camelus*. Merriam points out that *Camelops* possesses an accessory foramen, absent in modern camels, at the outer end of the postglenoid process. The glenoid region is broken off in the specimen, but this foramen is clearly visible in the broken end of the process. The close union of paroccipital and mastoid is well shown in this figure.

Brain case—posterior surface (*Fig. 3*).—The main point of interest here is the presence of large post-temporal openings, also characteristic of *Camelops*. These openings are quite small in *Camelus*. The distal ends of the paroccipital processes are directed downward and then inward, leaving a narrow space between them and the condyles,

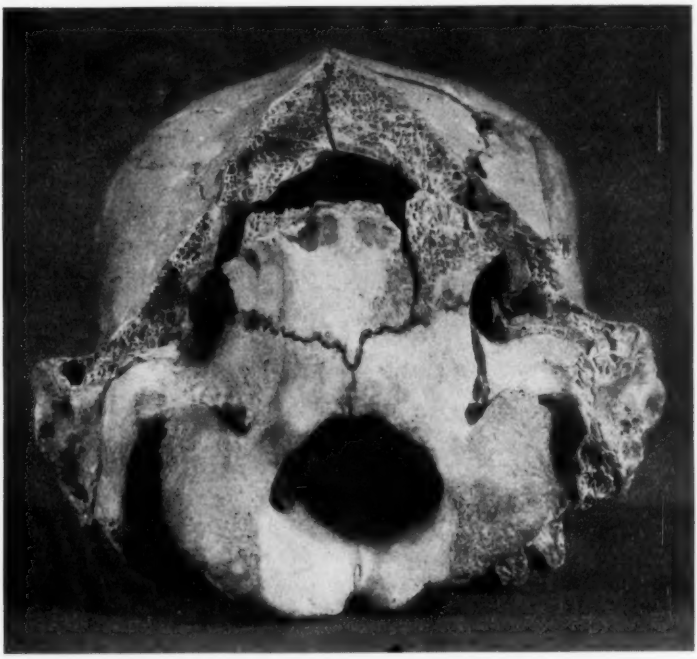

FIG. 3.—Posterior view of braincase, showing the large posttemporal openings and the location of the paroccipitals, $\times\frac{1}{2}$.

as in *Camelops*. These processes curve more outwardly in the Bactrian camel; the dromedary is somewhat intermediate.

Palate—ventral surface (*Fig. 4*).—Both sides of the posterior portion of the palate are preserved, but there is no contact between palate and braincase. M^3 is absent, and that portion of the maxilla which should contain its alveolus is broken off; the tooth may have

been still in process of formation in this young specimen. The molars present are broken off below the surface of the palate, making them appear somewhat smaller than would have been the case had they been preserved entire. The bony palate terminates opposite the end of m^2 in this specimen, much as in *C. hesternus* and the Bactrian camel, and in contrast with its somewhat greater prolongation posteriorly in *C. dromedarius* and the skull described by Merriam as "*C.*

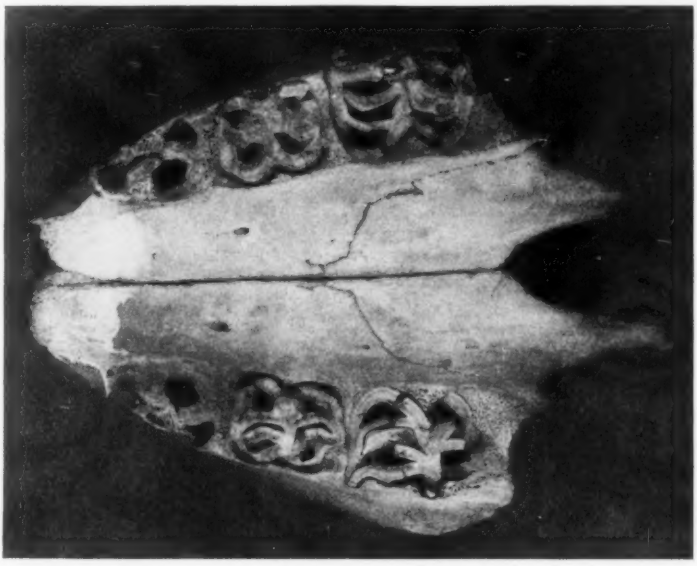

FIG. 4.—Ventral view of palate, $\times\frac{1}{2}$

near *hesternus*." The suture between palatines and maxillae is an irregular V, terminating anteriorly opposite the posterior lobe of m^1, as in *C. hesternus*. In both living camels and "*C.* near *hesternus*" the sutures meet more posteriorly, and usually with a more rounded contour.

Palatal region—lateral surface (*Fig. 5*).—Although little of the lateral surface of the facial region is preserved, the portion remaining affords valuable information. Near the lower posterior edge of the

original outer surface of the fragment is visible a rugose area which is the anterior end of the region of origin of the masseteric muscle. In living camels this area is situated somewhat higher up on the side of the face, while the ventral margin of the orbit is placed almost immediately above it. This cannot have been the situation here; for above this rugosity (where the external surface has been broken off) is visible that portion of the maxilla which contains the roots of m^2. The orbit must have been situated more posteriorly and dorsally.

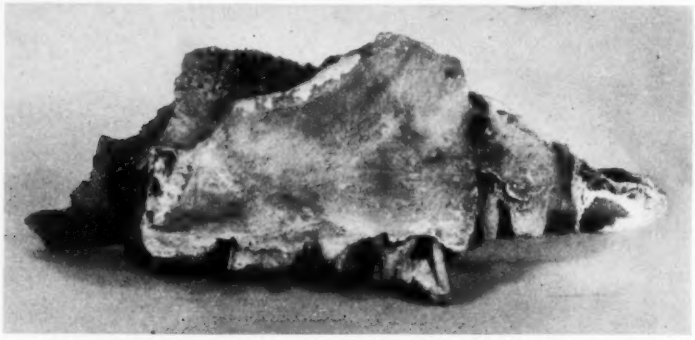

FIG. 5.—Lateral view of right half of palatal region, $\times\frac{1}{2}$. Low down on the outer surface the anterior end of the masseteric rugosity is visible. Above it may be seen the portion of the maxilla containing the roots of m^2 indicating that the orbit cannot have been located in the position found in *Camelus*.

This is the situation found *in Camelops;* Merriam has commented on this characteristic difference in position of the orbits between the extinct and living genera.

From the foregoing description it is obvious that the specimen differs from the living members of the genus *Camelus* in a considerable number of features of diagnostic value. *Auchenia* may be eliminated from consideration, not only because of size, but also through obvious structural differences. From the skull described by Merriam as "Camelops near *hesternus*" the specimen differs somewhat in the palatal region. From the skull assigned by that writer to *Camelops hesternus* it differs in no important feature whatever, although the present specimen (that of an immature animal) is somewhat smaller.

Merriam has discussed the taxonomy of the group; since the type of the species consists mainly of part of the inferior dentition, some doubt attaches to the identification of cranial material. But as far as our present knowledge goes, the specimen may be assigned to *Camelops hesternus*.

The significance of this find has been discussed in the pages of *Science*. We may repeat here only the obvious conclusion: that a native American camel, supposedly extinct since the early Pleistocene, has existed recently in the Great Basin region.

THE RELATION OF CHEMICAL COMPOSITION TO TEXTURE OF GROUNDMASS IN SILICEOUS LAVAS

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ABSTRACT

Fifty analyzed siliceous lavas, described in the literature, were studied to observe the relation of chemical composition to groundmass texture and kind of phenocrysts. It was found that the amount of excess silica in a rock determined the type of its groundmass; rocks with more than 26 per cent of quartz in the norm showed rhyolitic texture, and rocks with less than 26 per cent of normative quartz showed trachytic texture. Although most of the rocks showed a reasonable approach to the composition of Vogt's granitic anchi-eutectic, it was found that the kind of phenocrysts present were often not the kind to be expected from a melt striving to reach the anchi-eutectic composition. More accurate data are needed for a critical consideration of the anchi-eutectic theory.

Siliceous lavas crystallize with two fundamentally different types of groundmass texture: the one characteristic of rhyolites, with spherulitic and granophyric intergrowths of feldspar and silica (quartz or tridymite), or microgranular assemblages of quartz and feldspar; the other more typical of trachytes, with felted masses of tabular feldspar crystals and more or less indeterminable interstitial material. Porphyritic varieties may contain phenocrysts of quartz, orthoclase, plagioclase, and various ferro-magnesian minerals in either type of groundmass. Vogt[1] has suggested in several papers that, during crystallization of a siliceous magma, the rest-magma approaches a ternary anchi-eutectic composition. If this be the case, the final crystalline product of a siliceous flow-rock would be a record of the attempts of the residual liquid to attain this composition. Vogt did not specifically consider this textural expression in the lavas which he discussed. The writer has studied the relation be-

[1] J. H. L. Vogt, *Die Silikatschmelzlösungen*, Vol. I (1903), pp. 101–7; Vol. II (1904), pp. 113–28; "Über Anchi-eutektische und Anchi-monomineralische Eruptivgesteine," *Norsk Geol. Tidsskr.* Bd. I (1905), No. 2; "Physical Chemistry of the Crystallization and Magmatic Differentiation of Igneous Rocks, Pt. I," *Jour. Geol.*, Vol. XXIX (1921), pp. 318–50; "The Physical Chemistry of the Magmatic Differentiation of Igneous Rocks, Pt. II," *Vid.-Akad. Skrifter.* I. M.-N. Kl. (1926), No. 4.

tween texture and chemical composition of a number of siliceous flow-rocks described in the literature.

Fifty such rocks, for which sufficient data were available, were classified into two main groups, rhyolitic and trachytic, on the basis of the two types of groundmass. A number of the rocks had a glassy groundmass, but the analyses were used in the study because many of them showed phenocrysts of various kinds. Since the interest centers on the quartz and feldspar only, the composition of each rock was expressed in percentages of normative quartz, orthoclase, and plagioclase, recalculated to 100 per cent. The normative albite and anorthite were lumped together, since anorthite does not occur in any great quantity in most of these lavas. The composition of each rock was then plotted on a three-component diagram, with symbols to represent the type of texture (see Fig. 1).

First consider the data without regard to the presence or amount of phenocrysts. The most striking observation to be made is that the groundmass (if crystalline) of all rocks containing more than 26 per cent normative quartz is rhyolitic and that of rocks with less than 26 per cent quartz is trachytic. Only two rocks are found to be within 2 per cent of Vogt's anchi-eutectic point. Neglecting the quartz percentage, of the fifty rocks plotted, thirty-eight lie within 3 per cent of the feldspar ratio given in Vogt's anchi-eutectic, and only six rocks are more than 5 per cent in error.

The consideration of the amount and kind of phenocrysts is seriously limited by the lack of quantitative data in the rock descriptions. Of the twenty-four rocks containing normative quartz in amounts greater than 5 per cent in excess of Vogt's anchi-eutectic proportion, nine contain no phenocrysts, three contain feldspar but no quartz, and twelve carry varying amounts of both quartz and feldspar phenocrysts. Ideally, these rocks should all show quartz phenocrysts.

Three rocks have over 5 per cent normative plagioclase in excess of the amount required by Vogt's anchi-eutectic. Two of these (Nos. 4 and 50) have no phenocrysts and the other (No. 49) has phenocrysts of plagioclase and quartz. Orthoclase exceeds the anchi-eutectic amount by more than 5 per cent in the norms of three rocks, of which one (No. 19) carries quartz and orthoclase, and

two (Nos. 16 and 46) show both orthoclase and plagioclase phenocrysts.

Of ten rocks containing normative orthoclase and plagioclase in ratios approaching very nearly the anchi-eutectic ratio, three (Nos.

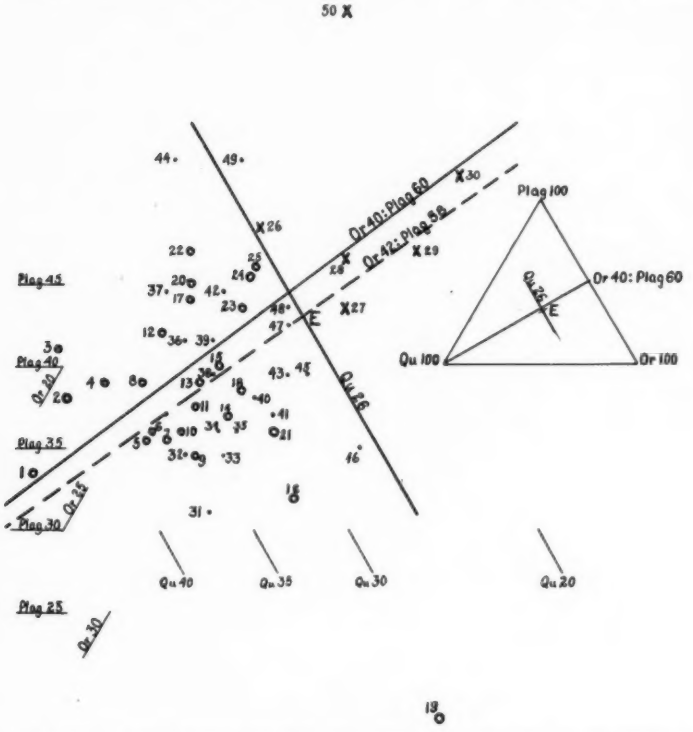

FIG. 1.—Enlarged central area of three-component diagram showing the composition of fifty rocks in percentages of normative quartz, orthoclase, and plagioclase. Rocks indicated by a circle have rhyolitic groundmass; those shown by a cross, trachytic groundmass; those marked with a dot have a glassy base. Intersection *E* of the line showing 26 per cent quartz and the line indicating a feldspar ratio of 42or:58plag is Vogt's anchi-eutectic point, 26qu:31or:43plag. Ratio 40or:60plag is Vogt's limit "not exceeded" by the composition of groundmass of flow-rocks.

5, 13, and 15) have quartz and orthoclase; one (No. 47) has quartz, orthoclase, and plagioclase; one (No. 28) has orthoclase and plagio-

clase; two (Nos. 6 and 48) have only plagioclase; and one (No. 11) has no phenocrysts. Data are not given for two rocks (Nos. 30 and 38). Theoretically these rocks should either have no phenocrysts or else both types of feldspar in equal amounts.

A survey of the other analyses in which the orthoclase-plagioclase ratio from the norm differs by less than 5 per cent from that of Vogt's anchi-eutectic shows a similar array of combinations of phenocrysts. Summing up the relation of the kind of feldspar to the kind of normative feldspar present in excess of the anchi-eutectic amount: of fourteen rocks with an excess of plagioclase in the norm, four have plagioclase as the only feldspar phenocrysts, five have both feldspars, and five have only orthoclase phenocrysts; of the thirteen rocks with an excess of normative orthoclase, five have orthoclase, five have both feldspars, and three have only plagioclase phenocrysts.

It is evident from this brief survey of these data that the kind of phenocrysts found in the siliceous flow-rocks are not to be perfectly explained by Vogt's anchi-eutectic theory. The rhyolitic lavas should be carefully studied with analyses made expressly for the purpose in order to obtain from them satisfactory evidence either for or against the existence of an anchi-eutectic in siliceous magmas. The writer feels justified in drawing only one definite conclusion from this study. It seems very evident that the percentage of excess silica in the magma in a large measure determines the texture of the groundmass of rhyolitic and trachytic lavas. Those rocks which have a rhyolitic groundmass are found to contain more than 26 per cent of normative quartz, and those which show a trachytic groundmass have less than 26 per cent of quartz in the norm.

A FOSSIL LAVA TUBE

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Volcanism produces many curious small structures, and one on the property of Mr. K. Hamada, at 1524 Sixteenth Avenue, Honolulu, seems worthy of description. Mr. Hamada reported to Bishop Museum, of Honolulu, that he thought he had a petrified tree, and this report was referred to me for a geologist's opinion. The accompanying pictures were made during the examination.

FIG. 1.—Side view of fossil lava tube

The general form is shown in Figure 1, and suggests that of the broken petrified trees in some of the national parks. A cross-section, as in Figure 2, shows bands of vesicles that are much like the growth rings of trees. Close examination shows that the bands do not go completely around and close on themselves as tree rings do. The greatest and least diameters of the ellipsoidal cross-section are about $4\frac{1}{2}$ and $3\frac{1}{2}$ feet. The total length shown in Figure 1 is about 40 feet, but fragments totaling as much more have rolled down the sides of the small ridge that is surmounted by the parts still in alignment. The long axis is parallel to the local slope of the lava flows. There is a very slight tendency toward radial jointing.

The origin of this object seems to be as follows: A lava tube had been made and was later permissively intruded by new lava. There was some motion of lava along the tube, which resulted in the segregation of gas vesicles in certain bands making a flow structure which simulates tree rings. The younger lava solidified under more hydrostatic pressure than do surface flows, and is therefore less vesicular

FIG. 2.—End view or cross-section of fossil lava tube

and decidedly more resistant than the surrounding rocks. The weaker surrounding rocks have been removed by erosion, and the resistant filling of the tube remains. The low ridge on which the aligned parts lie seems to be due to the protective effect of this resistant capping. In places the floor as well as the sides of the tube has been removed so that the overlying parts of the filling have dropped a little out of alignment. Other parts of the filling have even rolled down the sides of the ridge.

Wentworth[1] gives a brief account of similar features on the

[1] Chester K. Wentworth, "The Geology of Lanai," *Bernice P. Bishop Museum Bull. 24* (1925), p. 50.

island of Lanai and calls them "lava tube casts." His interpretation is essentially like that given here, though both were reached independently.

One hesitates to add a new name to the geologic glossary, but it is perhaps allowable to christen this a "fossil lava tube." Fossils should, in the strictest sense, be marks of once living things, but we have the precedent of "fossil rain prints" for inanimate objects.

A short description of lava tubes may not be out of place here. The basaltic flows of Hawaii, as in other volcanic regions, usually spread over wide belts, but during most of the active stage the moving lava confines itself to a narrow central channel, except at the advancing edge, where it divides into various distributaries or "toes." The channels vary greatly in size. They usually remain open at the top, but sometimes a crust develops on the surface of the liquid-lava stream and forms the roof of a "lava tube" or tunnel through which the liquid lava continues to flow for a time. When the supply of lava is eventually shut off at the source, the liquid lava may drain out, leaving an open tube or tunnel. These lava tubes vary greatly in size. The largest of which I know are 10–20 feet high, and 20–30 feet wide. There are also miniature lava tubes in the minor distributaries, or toes, of pahoehoe flows, which are so small as to be described in terms of inches. The "fossil lava tube" here is of intermediate size.

ON THE FORMATION OF HOARFROST AND ITS RELATION TO GLACIAL GROWTH

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Upsala University

In connection with my glaciological researches in the Horung Massif in Norway,[1] which have been carried on for many years, the Meteorological Office of that country, under the direction of Dr. J. Bjerknes, has built a small observatory on the summit of Mount Fanaråken, which belongs to the Horung Massif. This massif is situated in Jotunheim, the greatest high-fell region in central Norway, 20 kilometers from the innermost part of the Sogne Fjord and 180 kilometers from the open sea. On June 23, 1928, I reached the observatory, 2,050 meters above sea-level, and lived there for nine days. During this period the temperature varied between $+1°$ and $-5°$ C., the wind was from the southwest the whole time, and, with the exception of one or two intervals lasting a few hours, the summit was covered with clouds. These climatic conditions were exceptional for the end of June and the beginning of July. They were more in accordance with the conditions prevailing in October and November.

A matter of special interest during my stay on the summit was the immense formation of hoarfrost. When the weather was calm, only a slight formation took place; but as soon as the southwesterly wind began, there were deposited on the windward side of all the objects above the ground thick sprays of hoarfrost. This was especially the case on surfaces which were not previously covered with snow, such as the walls and backstays of the observatory, steeply projecting parts of the rock-ground, etc. This formation of hoarfrost increased with the rising force of wind and attained its culmination during the storm that raged from the afternoon of June 29 until the morning of July 2. The anemometer of the observatory was not in working order; but I estimated the force of the wind, when it was greatest, at about 25–30 meters per second; the mean

[1] "Physicogeographical Researches in the Horung Massif, Jotunheim, under the Direction of H. W:son Ahlmann. I–VI," *Geografiska Annaler*, 1923, 1927, 1928.

force would seem to have amounted to 15–20 meters per second. During this storm not only was hoarfrost deposited on the objects projecting above the ground, but also the great snowfield that covered the summit was covered with a carpet of hoarfrost leaves, some of them measuring as much as 1 decimeter in length, 4–5 centimeters in breadth, and 1 centimeter in thickness.

Hoarfrost grows most rapidly, at least in most cases, on surfaces that are covered neither with snow nor with rime.[1] After the sprays

FIG. 1.—The meteorological observatory on Fanaråken covered by hoar frost, July 2, 1928.

of hoarfrost have grown out to a certain length, they grow slowly. This was easy to observe, for if I scraped the backstays clean for a certain stretch, the rime grew immediately on this space so rapidly that it was soon as thick as on the parts that had not been scraped. But the wind itself can break off the hoarfrost sprays, and as soon as the temperature rises above 0° C. they fall off rapidly. Thus it is very difficult to obtain values for the absolute magnitude of the formation of hoarfrost. But it is very highly promoted by fluctuations between temperatures above and below the freezing-point while there is a moisture-bearing wind blowing.

During the storm (June 29 to July 2) I twice cleaned the great

[1] Hellmann, "System der Hydrometeore," *Veröffentl. d. k. preuss. meteor. Institut, Abhandl.* (Berlin), Bd. V (1915), p. 2.

thermometer case standing outside the observatory, both outside and inside; but after each time not only was it covered rapidly with hoarfrost but it was also filled entirely with its porous masses. Hence no instruments could function inside it even for a short time. On the backstays of the observatory, on scraped parts at a distance of 1.5 meters from the ground, there were deposited in the course of three hours, sprays of hoarfrost measuring 10–20 centimeters in length and 5 centimeters in thickness at the top end facing the wind. If we

FIG. 2.—Hoar frost on the windward side of a projecting part of the rock ground on Fanaråken, July 1, 1928.

assume for the sake of simplicity that the hoarfrost sprays had a conical shape, their volume amounted to 98 cubic centimeters. If the specific weight of the hoarfrost on this occasion is put at 0.5, their water-content in round numbers was 50 cubic centimeters. The surface of the backstay facing the wind on which this hoarfrost was formed measured 1 centimeter. This means a precipitation in the form of hoarfrost of no less than 0.046 millimeters per millimeter and second.

For reasons previously given, it is of course not correct to multiply this value by the total number of seconds during which the storm lasted. But in view of the fact that the temperature rose above the freezing-point on one or two occasions during the storm, and that the hoarfrost formed on such occasions partly fell off, so that fresh

hoarfrost could be rapidly formed again when the temperature fell, I regard it as probable that during the three days in question there was deposited on the projecting objects on the summit of Fanaråken, on the sides facing the wind, hoarfrost with a water-content of 1.5 meters per unit of surface. The hoarfrost deposited on the level snow surfaces formed only a small fraction of this and may probably be computed at only 10 or 20 millimeters. It is not possible to form any exact idea of the total amount of hoarfrost that was formed during the period from June 29 to July 2, but from the figures above-cited it would seem to be clear that that amount must have been very considerable. During the other days of my stay on Fanaråken also the deposit of hoarfrost must have been great, though not comparable with that during the storm. The lower limit for the formation of hoarfrost would seem to have varied between 1,800 and 1,900 meters above sea-level during the period from June 23 to July 2.

A study of the huge snowdrifts that covered both the southwest side of the observatory and the slopes of the summit in the same direction showed that probably they consisted for the most part of hoarfrost. As far as can be judged, therefore, it is evident that the freezing of the moisture in the air into hoarfrost on the summit of Fanaråken is of extraordinary importance for its snow conditions. I even venture to believe that the deposit of hoarfrost plays a greater part than the fall of snow.

This holds good especially during the autumn, when the southwesterly storms are most numerous; but similar conditions would seem to occur often in the winter also. This is confirmed by an observation made by a couple of climbers on Store Skagastölstind (2,404 meters) one Easter. The summit of the mountain was covered by hoarfrost several meters deep. During my stay at the observatory it could be observed during the short intervals of clear weather that the extremely steep summits of the adjacent peaks of the Horung Massif became shrouded in an ever thicker white gown, in spite of the fact that the actual fall of snow was extremely insignificant. I suppose that on the higher levels of the western massif on the Jotunheim, which are exposed to the moisture-bearing southwesterly wind, a very great part, perhaps the greatest part, of their snow is supplied by hoarfrost. Thus hoarfrost plays a considerable part in the feeding of the glaciers there.

There is every reason to suppose that the importance of the hoarfrost is yet greater on the mountains situated nearer the sea. In that case this would hold good especially for the Alfob Glacier south of the mouth of Nord Fjord, for the western parts of the Jostedal Glacier, the largest glacier on the main land of Europe, and for Svartisen Glacier in Norwegian Nordland. The meteorological stations near these glaciers give a couple of thousand millimeters as the yearly precipitation. According to my calculations,[1] however, the yearly precipitations on these glaciers must amount to 5,000–6,000 millimeters. The difference between these values would certainly seem to be largely due to the formation of hoarfrost at the higher levels.

Great formations of hoarfrost have long been known from the Brocken in Germany and the Ben Nevis in Scotland. As regards the Scandinavian mountains, A. Hamberg's observations[2] in the Sarek Fells in Lapland directed particular attention to the importance of hoarfrost. H. Köhler has since made a closer study of it and, in addition to the work previously cited, has published one or two others, of which the most important in this connection is "Zur Kondensation des Wasserdampfes in der Atmosphäre."[3] During a journey in the Lofoten Islands in March, 1917, I observed that the lower limit for the formation of hoarfrost there lay about 750 meters above sea-level. J. W. Sandström[4] has pointed out the great importance of this fact for our knowledge of the meteorological conditions during the winter over the northern part of Scandinavia. In a short article on the connection between continental changes of level and the Pleistocene inland ice around the North Atlantic, Professor B. Helland-Hansen and I[5] have pointed out the great importance of hoarfrost in bringing this inland ice into existence. The members of the ex-

[1] "Précipitations annuelles de la Péninsule Scandinave" (in Swedish with a French résumé), *Meddelande fr. Statens Meteorologisk-hydrografiska Anstalt.* (Stockholm), Bd. III (1925), p. 4.

[2] A. Hamberg, "Die Eigenschaften der Schneedecke in den Lappländischen Gebirgen," *Naturwissensch. Untersuch. d. Sarekgebirges*, etc. (Stockholm), Bd. I (1907), p. 3.

[3] *Geofysiske Publikationer* (Kristiania; Oslo) Vol. II (1922), p. 6.

[4] H. W:son Ahlmann och J. W. Sandström, "Den övre rimfrostzonen i Lofoten," "*Naturen*" (Bergen, 1917).

[5] *Geologiska Föreningens Forhandlingar* (Stockholm, 1918).

cursion of the Twelfth International Congress of Geographers in Wales in the summer of 1928 were surprised to find at what surprisingly low altitude local glaciers had lain in those districts during the last Ice Age. The same very low limit of glaciation (about 300 meters) I had later occasion to observe in the lake district of Cumberland also. Without wishing to enter upon any explanation, I should nevertheless like to throw out the suggestion that within these distinctly maritime regions on the Atlantic, the formation of hoarfrost possibly may have played a great part in glacier formation during the Ice Age.

REVIEWS

"On the Echelon Structure of the Japanese Archipelago." By SADAKAZU TOKUDA (Geologist, Mitsui Mining Co., Tokyo). *Japanese Journal of Geology and Geography*, Vol. V, pp. 41–76, with maps, diagrams, and photographs of experimental results.

"Torsional Form of the Earth Surface and the Great Earthquake of Sagami Bay." By SAKUHEI FUJIWARA. *Journal of the Meteorological Society of Japan*. Year 43, pp. 1–7, with diagrams and photographs of experimental results.

The article on "Echelon Folds and Arcuate Mountains" by Dr. Link in a recent number of the *Journal of Geology*[1] places on record some of the results of experiments arranged to determine the nature of folds produced by pressure transmitted by the front of a curved body advancing in a definite direction, or by the straight front of a body advancing against materials that differ in rigidity. It appears that differential pressures, shearing, and echelon structures result in either case, whether the inequality of pressure results from the form of the advancing body or from the diverse resistances of the compressed body. It is of great value to students to have thus clearly presented the conditions which are of somewhat general occurrence in nature.

Dr. Link's results are part of the series of experimental demonstrations which are coming out of the work in the geophysical laboratories of the University of Chicago, under the direction of Professor Rollin Chamberlin. They will deservedly attract the attention of students of tectonics, who will welcome definite observations on structures of obscure and debatable origin. They do not stand alone in their class, however, and it is desirable to call attention to two similar studies, which because they are described in Japanese publications only (although both in English) may not be readily accessible to American geologists.

Mr. Tokuda, the author of the paper "On the Echelon Structure of the Japanese Archipelago," is a mining engineer with a remarkably broad knowledge of geologic theory, both in Japanese and foreign languages. In possessing the former he has an advantage over the majority of geologists

[1] Theodore A. Link, *Jour. Geol.*, Vol. XXXVI (1928), pp. 526–38.

from other countries, since they are unfortunately shut out from the mine of information contained in Japanese publications. The reviewer first learned to appreciate how serious that handicap is when attending the Third Pan-Pacific Congress at Tokyo in October, 1927. He there met Mr. Tokuda among others, and, studying the Japanese islands on the spot, was struck with the significance of the echelon structure.

The paper first describes three of the major arcs of islands that skirt the western margin of the Pacific from Kamchatka to Formosa, namely, the Kurile Island arc, the Luchu Island arc stretching from Southern Japan to Formosa, and an inner arc that springs from the northwest corner of Formosa (Taiwan). The submerged arc that springs from Central Japan about longitude 140, and extending south, southeast, and southwest passes through the Marianna Islands to Halmahera (Jilolo) Island, is next discussed. The writer then returns to Central Japan and describes the echelon structure of certain volcanic chains as well as of the folds in the Echigo coal field.

Mr. Tokuda distinguishes different geometrical arrangements of the echelon structures, as, for instance, (*a*) inclined from below upward toward the right, and (*b*) inclined from below upward toward the left with reference to the direction of offsets; he discusses the amount of offset and its variation, and goes into other details for which the original paper must be examined.

The article is illustrated by excellent outline maps which give the submarine contours determined by the surveys of the Japanese Hydrographic Department and also by some thirty photographs of folds produced in rice paper by pressure with the finger tips, a characteristically delicate but suggestive mode of procedure.

Mr. Tokuda concludes:

> Attempts have been made by many geologists to find the mechanism of formation of arcuate mountains. For this purpose the present experimental study is of some use. Japanese islands are composed of a number of echelon folds. It has been shown experimentally that such folds can be formed simply by lateral pressure. When an orogenic lateral pressure is applied on earth's crust there is formed a symmetrical echelon arc. The number of echelon folds increases toward the end of the arc, but decreases toward the center of the arc. When an obstacle lies near the end of an arc many folds develop there in close duplication, as in the west part of Kyushu and in the east part of S.W. Japan. There the landmasses of palaeo-Japan nearby worked as an obstacle. The folds in the oilfields in Echigo and Tohuko districts were developed freely in thick and soft Tertiary terrain without any obstacle.

Our experimental results justify Suess view concerning the direction of the arc producing force; while Hobb's and von Richthofen's views are in contradiction to our experimental results. If two or more arc-making forces act together on the earth's surface there is produced syntaxis or "*Flankenkettung.*" Various types of arcs have been produced in our experiments. These may be regarded as modifications of the simple symmetrical echelon arcs. In Nature, more modifications of echelon arcs are expected, being affected by many factors. It is hoped the present experiments may be of use for the solution of the problems connected with the symmetrical echelon structure as seen in the archipelagoes of Eastern Asia.

Mr. Fujiwhara's paper presents (rather inadequately, one suspects) the author's views on the formation of tension cracks and shearing planes. He has experimented with a slab of putty laid across the crack between two boards, and he figures its distortion when the boards are slid past one another as if horizontally along a vertical fault. The effect is that postulated by H. F. Reid for the distortion along the San Andreas fault before the 1906 earthquake. A map of Sagami Bay is given to demonstrate the areas affected respectively by uplift and subsidence. It is to be regretted that the author's command of English is not as perfect as that of his colleague and that it is possible his statements do not do justice to his full meaning.

It is interesting to observe that both the Japanese authors and Dr. Link have chanced to use the tectonic map of the Jura to illustrate their several theories of echelon structure.

BAILEY WILLIS

Foraminifera, Their Classification and Economic Use. By JOSEPH A. CUSHMAN. Sharon, Mass., *Special Publication No. 1* (Cushman Laboratory for Foraminiferal Research), April, 1928. Pp. 401; pls. 59. $5.00.

According to the author's own description, this volume is merely "an introductory treatise on the subject, both from the point of view of the teacher and student as well as that of the worker on economic problems." This modest depreciation is not likely to mislead micropaleontologists! The publication is actually the judiciously abridged summary of the significant results of twenty years of research on the Foraminifera by one who had appreciated their significance and mastered many of their intricacies long before the oil industry had elevated them to their present high position of economic and scientific importance. Perhaps it is not

extravagant to say that no group of invertebrates of comparable size has ever been treated more comprehensively or authoritatively. Dr. Cushman has not been content merely to read descriptions and examine figures; his studies have taken him to many museums at home and abroad, so that he has been able to examine the type specimens (or authentic material) of nearly 95 per cent of the genera he has considered. This is only one of the many reasons why readers will be inclined to feel that the more than four hundred genera which are described are valid, that the nearly two hundred generic terms which have been reduced to the synonymy properly are so placed, and that the few genera which are not described are very doubtful, or represented by rare forms whose types are inaccessible.

Approximately three-fourths of the book is devoted to a systematic description of the various genera, but chapters dealing with "Trimorphism," "The Test," "Methods of Study," "The Living Animal," and similar subjects are also included. Under the discussion of each genus there is given either the genoholotype or a designated genotype, the common synonyms, the description, and the geologic range. Figures are included for practically all of the genera, and wherever possible the type figure has been utilized. In cases where the latter has not been adequate for a clear comprehension of the genus, a later figure has been substituted. For the sake of comparison, figures of several species of one genus are included in a number of instances, and several of the plates are arranged to show the relationships of the genera within a family. All of the figures of the fifty-nine plates are well drawn and conveniently arranged. The plates themselves ordinarily are placed as near as possible to that portion of the text which describes the genera portrayed. A key to the families is included, and generic keys are also given for the larger families.

Dr. Cushman has recognized forty-five families in a natural classification which is based on the stages of development in the microspheric forms and the past and present history of each group. This classification will supplant the one proposed by Brady in his *Challenger* report for 1884 which, with its ten families distinguished by resemblance of form in adult tests, has been quite generally used heretofore. The earlier classification was artificial in that it grouped together forms which have features in common in the adult stage, but which, as has been shown by Cushman and others, have had very different developmental stages. All of the families recognized, except the Allogromiidae, play a part in the fossil record, but in addition the Keramosphaeridae and the Neusinidae

are only represented in the latest Tertiary deposits. Both of these families, as well as the Allogromiidae, are wholly composed of species which are living today.

The division dealing with the Fusulinidae was contributed by Dr. Yoshiaki Ozawa; that describing the Orbitoididae, by Dr. T. Wayland Vaughan.

The Bibliography of thirty pages is not only carefully selected, but it has been so arranged as greatly to facilitate its use. Those papers dealing with the recent and fossil forms are grouped under periods by geographic divisions, and under these groupings the papers are arranged alphabetically by authors. Papers on structure, nomenclature, and similar headings are also listed alphabetically by authors. The volume is well bound, clearly printed, and the plates are uniformly well reproduced.

Criticisms of such a work can only be of a trivial nature. The eight subgenera of Orbitoididae, however, which are the only unfigured forms, might well have been illustrated, if only for the sake of uniformity. The explanation of the plates would have been somewhat improved had text references to the genera been added, although this is a relatively minor omission since, as mentioned before, the majority of the plates are conveniently placed. The earlier chapters suffer somewhat from a lack of figures, and several of the problems might have been more clearly presented to the general reader had illustrations been utilized. It is to be regretted also that the results of the studies of the Fusulinidae recently made by Dunbar and Condra and by Lee apparently did not appear early enough to be taken into consideration by Dr. Ozawa, but it is the fate of all such monumental works to be at least slightly out of date when issued.

Dr. Cushman has taken us into his confidence, shown us his tools, methods, and results, and the gratitude and praise of paleontologists the world over are quickly forthcoming. But what will be quite generally overlooked is the great indebtedness of the oil industry itself, for much of the material now made available to all in *Foraminifera, Their Classification and Economic Use* had a very high money value. Many a less publicly spirited man would have divulged it only at a price.

CAREY CRONEIS

The Geology of Venezuela and Trinidad. By RALPH ALEXANDER LIDDLE. Fort Worth: J. P. MacGowan, 1928. Pp. 552; figs. 22; pls. 83. Bibliography. Map in pocket.

The geology of Venezuela and Trinidad is as yet insufficiently known to permit accurate regional correlations of the stratigraphy, physiogra-

phy, or structure, but the author of this book, by bringing together the available data, has approached this goal. About 10 per cent of the text is devoted to the major physiographic provinces of Venezuela; one-half the volume is devoted to sedimentary deposits which are of Paleozoic, Mesozoic, and Cenozoic age; while the concluding chapter on economic geology comprises about 35 per cent of the text.

The Paleozoic occurs in a few restricted localities, whereas younger formations are abundant. Seas which gradually encroached during the Paleozoic and early Mesozoic spread more rapidly in the Cretaceous, depositing clastics below and above a mid-Cretaceous limestone series. Over much of the country a definite structural unconformity exists between the Cretaceous and Eocene, between which periods some deformation took place in the Andine chains.

The Eocene sediments are exposed chiefly along the flanks of the Venezuelan Andes and Coast ranges, where they comprise littoral and lacustrine sandstone and shale underlaid by coal and overlaid by marine conglomerate.

Unconformable on the Eocene rest 1,000–3,000 feet of black shale and 1,000 feet of coralline-reef limestone of Oligocene age.

The Lower Miocene, separated by an unconformity from the Oligocene, consists of fluviatile, lagoonal, and continental deposits. Sediments of the middle and upper portions are deltaic, and characterized by lateral variation. A widespread unconformity is present in the Middle Miocene as a result of folding, uplift, and erosion which accompanied the major deformation of the Andes. Orogenic disturbances of lesser intensity mark the close of the period.

Over a large part of Venezuela the Pliocene appears to have been a time of erosion and was followed by gentle orogenic movements.

The metamorphic rocks are Proterozoic (Archeozoic?), Paleozoic, and basal Cretaceous in age. Granitic gneiss and gneissoid granite of igneous origin compose the older rocks, exposed throughout the extensive province of the Guiana highlands, south of the Orinoco River. They are thought to be continuous below the upper part of the Orinoco embayment, since they reappear in the Venezuelan Andes as a gneissoid granite core and are present in the Periza Mountains of the Venezuelan-Colombian frontier, and in the Cordillera Oriental, in which localities they are overlaid by sediments.

Paleozoic metamorphic rocks, some 2,000 feet in thickness, and of sedimentary origin, consist of iron-bearing quartzites, gneissoid schists, and phyllites. These occur as infaulted blocks in the Paleozoic basement complex and therefore have the same regional distribution.

The basal Cretaceous metamorphics have an estimated thickness of 3,000–4,000 feet, and are composed of schist, schistose slate, and gneiss. They outcrop in the coast ranges and south of the Orinoco.

Igneous rocks are of two types, acidic and basic. The former are largely plutonic granites of pre-Paleozoic age and the latter post-Cretaceous, shallow-depth, basaltic intrusives and flows. This group of rocks covers a relatively small part of the country, although distribution is widespread.

The pages devoted to the structural geology of Venezuela deal only with the major features of the country. The metamorphic mass of the Guiana highlands, underlying the area between the Amazon and Orinoco rivers, is anticlinal. The Amazon occupies a depression in these formations which reappear to the south. Southward thrusts from the Caribbean Sea against the Guiana mass have produced anticlinal zones of folding which are arcuately arranged with respect to the northern edge of the mass. The ranges are the Venezuelan Andes, Caribbean Coast Range, and Northern Range of Trinidad.

A gentle eastward-tilted syncline between the Caribbean Coast Range and the Guiana highlands, occupied by the Orinoco, is filled with Paleozoic and Tertiary sediments, the older formations being progressively exposed westward.

The Maracaibo Basin is a north-south syncline, flanked by the Andes on the east, south, and west. At the southeast end of the depression is a divide which, until the close of the Eocene, afforded a connection between the Maracaibo and Orinoco basins.

Of the economic products petroleum and asphalt are most important, whereas coal is widely scattered, of poor grade, and of little commercial value. Since the geology of the Maracaibo Basin area and the producing structures of the oil fields is largely confidential information of the operating companies, the author has given only a summary account of the various fields, under the following headings: (*a*) "Location and Accessibility," (*b*) "Date of Discovery," (*c*) "Structure," (*d*) "Producing Horizon," (*e*) "Character of the Oil," (*f*) "Production."

Eighty-seven pages are devoted to the geology of Trinidad, which is treated in the same manner as Venezuela. The island is crossed by three separate ranges—a northern, a central, and a southern—the former attaining a height of 3,000 feet. The northern range is composed in large part of metamorphic rocks, resembling those found in the Caribbean Coast Range of Venezuela. The sedimentary formations are similar to those of eastern Venezuela and have been correlated in some cases with

them. The author believes that Trinidad was joined to the mainland until the middle of the Miocene.

Asphalt is of greatest economic importance, and petroleum is produced in small amounts.

The text is well illustrated with photographs, maps, and sections. A pocket map showing the areal geology, correlation, and stratigraphic column of Venezuela is valuable. A useful and extensive Bibliography is wisely included.

RUTHVEN PIKE

North America. By I. C. RUSSELL. Second Edition. New York: Oxford University Press, American Branch, 1927. Pp. 435; maps 7; illus. 39. $4.25.

The stated aim of this book is to give a condensed account of the leading facts about the North American continent which are the most important to a geographer. Each chapter deals with a broad subject. These subjects are entitled: "The Margin of the Continent," "The Topography of the Land," "Climate," "Plant Life," "Animal Life," "Geology," "The Aborigines," and "Political Geography." Each topic is presented in a very readable manner and in a broadly general way. The text is accompanied by numerous excellent maps and figures.

It is interesting to the glacial geologist to note that Russell (Plate V, opp. p. 316) has used the nomenclature of the principal ice invasions of the Pleistocene as the names were originally given, namely, I, Kansan (earliest known stage of ice advance); II, Iowan (second stage of ice advance); III, Illinoian (third stage of ice advance); and Wisconsin (fourth stage of ice advance). These names, thus used, have priority, and regard for the recognized rules of priority as well as the appropriateness and fitness of names for the ice advances described, calls strongly for a revision of the present modified usage and a return to this original and more appropriate nomenclature. It is most unfortunate that misconception and blundering has led to an unwarranted transfer of the name Iowan from the drift of the second ice invasion (the most conspicuous drift of the state of Iowa) to a thin, later drift which has since been differentiated. It will be much better for the Pleistocene geology of the future to go back to the original nomenclature and to find a new name for the thin cover-beds of northeastern Iowa. Russell's map, however, follows present-day maps in using the term Iowan (second drift) for the much younger surface drift of northeastern Iowa, which is inconsistent with his classification.

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